On efficient signal processing algorithms for signal detection and PAPR reduction in OFDM systems

Dissertation submitted to the

National Institute of Technology Rourkela

in partial fulfillment of the requirements of the degree

of

Doctor of Philosophy

by

Prasanta Kumar Pradhan

June, 2016

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2 June 2016

Supervisor's Certificate

This is to certify that the work presented in this dissertation entitled ***"On efficient signal processing algorithms for signal detection and PAPR reduction in OFDM systems"*** by ***"Prasanta Kumar Pradhan"***, Roll Number 508EC102, is a record of original research carried out by him under my supervision and guidance in partial fulfillment of the requirements of the degree of *Doctor of Philosophy in Electronics and Communication Engineering.* Neither this dissertation nor any part of it has been submitted for any degree or diploma to any institute or university in India or abroad.

Sarat Kumar Patra

to my parents, my wife and my son

Declaration of Originality

I, Prasanta Kumar Pradhan, Roll Number 508EC102 hereby declare that this dissertation entitled ***"On efficient signal processing algorithms for signal detection and PAPR reduction in OFDM systems"*** represents my original work carried out as a doctoral student of NIT Rourkela and, to the best of my knowledge, it contains no material previously published or written by another person, nor any material presented for the award of any other degree or diploma of NIT Rourkela or any other institution. Any contribution made to this research by others, with whom I have worked at NIT Rourkela or elsewhere, is explicitly acknowledged in the dissertation. Works of other authors cited in this dissertation have been duly acknowledged under the section "Bibliography". I have also submitted my original research records to the scrutiny committee for evaluation of my dissertation.

I am fully aware that in case of any non-compliance detected in future, the Senate of NIT Rourkela may withdraw the degree awarded to me on the basis of the present dissertation.

June 2, 2016
NIT Rourkela

Prasanta Kumar Pradhan

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List of Abbreviations

A. List of Acronyms

AdaBoost Adaptive Boosting

ADSL Asymmetric Digital Subscriber Line

AWGN Additive White Gaussian Noise

BER Bit Error Rate

BLUE Bayesian Linear Unbiased Estimation

CCDF Complementary Cumulative Distribution Function

CDF Cumulative Distribution Function

CDMA Code Division Multiplexing Access

CF Crest Factor

CIR Channel Impulse Response

CSI Channel State Information

DAB Digital Audio Broadcast

DCT Discrete Cosine Transform

DDCE Decision Directed Channel Estimation

DFT Discrete Fourier Transform

DSL Digital Subscriber Line

DVB Digital Video Broadcasting

EM Expectation maximisation

FDM Frequency Division Multiplexing

FFT Fast Fourier Transform

GA Genetic Algorithm

ICI Inter Carrier Interference

IDCT Inverse Discrete Cosine Transform

IEEE Institute of Electrical and electronics engineers

IFFT Inverse Fast Fourier Transform

ISI Inter Symbol Interference

LAN Local Area Network

LS Least Square

LTE Long Term Evolution

MAMPS Multi-Amplitude-Multi-Phase Signal

MAN Metropolitan Area Network

MCM Multicarrier Communication

MIMO Multi-Input-Multi-Output

ML Maximum Likelihood

MMSE Mean Square Error Estimation

MSE Mean Square Error

MUD Multi User Detection

OFDM Orthogonal Frequency Division Multiplexing

PAPR Peak to Average Power Ratio

PDF Probability Density Function

PTS Partial Transmit Sequence

QAM Quadrature Amplitude Modulation

QPSK Quadrature Phase Shift Keying

RF Radio Frequency

SAS Successive Addition Subtraction

SDMA Space Division Multiple Access

SER Symbol Error Rate

SLM Selective Mapping

TI Tone Injection

TR Tone Reservation

VBLAST Vertical-Bell Laboratories Layered Space-Time

Wi-Fi Wireless Fidelity

WiMax Worldwide Interoperability for Microwave Access

WLAN Wireless Local Area Network

B. List of Symbols

τ_i — ith Path delay

$\tilde{b}^V$ — Optimised phase vector in PTS technique

$\tilde{U}$ — Optimised phase vector in SLM technique

f_{Di} — ith path Doppler shift

$g(t)$ — Transmitted Pulse

$H(k)$ — Frequency domain channel

$h(n)$ — Channel Impulse Response

H_p — Channel at pilot locations

N — Number of subcarriers

N_g — Length of guard interval in samples

N_p — Number of Pilot carriers

N_r — Number of receiver antenna

N_t — Number transmit Antenna

p_r — Probability

T_s — OFDM symbol duration

V — Number of sub blocks in PTS technique

$W(k)$ — AWGN in frequency domain

$w(n)$ — AWGN in time domain

$x(n)$ Time domain signal

X_p or x_p Data at pilot location

Z_{max} Crest factor

$X(k)$ Multi-Amplitude-Multi-Phase Signal by M-ary modulation process

$x_g(n)$ Guard band signal

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1

Background and Motivation

"To invent something is to find it in what previously exists."

Brian Arthur

Contents

Orthogonal Frequency Division multiplexing (OFDM), the multi-carrier modulation (MCM) technique, has been seen to be very effective for communication over channels with frequency selective fading. It is very difficult to handle frequency selective fading in conventional communication receivers as the design of the receiver becomes hugely complex. OFDM technique efficiently utilizes the available channel bandwidth by dividing the channel into low bandwidth contineous channels. Instead mitigating frequency selective fading as a whole, OFDM mitigates the problem by converting the entire frequency selective fading channel into number of narrow bandwidth flat fading channels. Flat fading makes the receiver easier to combat channel tracking and Inter Symbol Interference (ISI) by employing simple equalization schemes.

1.1 Introduction

Spread spectrum modulation has been the basis for majority of proprietary communication and boadcasting technology including IEEE 802.11 wireless local Area Networks (WLANs), ZigBee, Ultra Wide Band (UWB) and others. Through the use of frequency hopping and direct sequence, these WLANs provide data rates from 1 to 11 Mbps. Regardless of these relatively high data rates, there there has been an increasing demand of higher data rate for wireless broadband Local Area Networks (LANs) and Metropolitan Area Networks (MANs). Because of relatively inefficient use of bandwidth, spread spectrum systems did not satisfy the even higher data rates that multimedia applications required. In addition, multimedia applications operating outdoors or within industrial environments require a wireless network capable of operating more effectively in "RF hostile" areas. Consideration of more efficient and robust OFDM technology became a viable option for high data rate multimedia implementations. OFDM, sometimes referred to as multi-carrier or discrete multi-tone modulation, utilizes multiple sub-carriers to transport information from one user to another.

OFDM is a form of signal modulation that divides a high data rate modulating stream to many slowly modulated narrowband close-spaced sub-carrier. In this way narrowband sub-channels, carried by close-spaced sub-carrier, becomes less sensitive to frequency selective fading. In some respects, OFDM is similar to conventional frequency-division multiplexing (FDM). The difference lies in the process in which individual sub-carriers are modulated and demodulated. Priority is also given to minimize the interference and crosstalk among the channels and symbols comprising the data stream. Generally all channels are handled together and individual channels are never handled separately.

1.2 Application of OFDM

A formidable growth of demand for high data rate multimedia based services and high spectral efficiency are the key requirements for the continued technology evolution in future wireless communications. In recent past, several advancements have been incorporated for 3G wireless communication systems for enhancement of the data rate and the system performance (e.g., high speed downlink packet access (HSDPA) in wideband code division multiple access (WCDMA) systems, 1x evolution-data and voice (1xEV-DV) for cdma2000 systems). Continuous proliferation of wireless multimedia applications and services such as video teleconferencing, network gaming, and high quality audio/video streaming requires very high data rate. At present, it is apparent that the existing 3G wireless systems with its optimum capacity will be unable to support with this ever increasing demand for broadband wireless services. The next generation wireless communication systems (namely, fourth generation (4G) or beyond 3G (B3G) systems, LTE, and fifth generation (5G)) are expected to support much higher data rate services compared to evolving 3G systems (up to 100 Mbit/s in outdoor environments and up to 1 Gbit/s in indoor environments). LTE-A is supposed to support up to 1Gbit/s data rate and gigabit wireless communication for millimeter wave communication known as 5G is expected to support data rate of beyond 1 Gbit/s. In order to achieve this high data rate, the major technical challenges will be achieving high spectral efficiency, handling high frequency-selectivity due to the use of large bandwidth, handling high PAPR as more number of subcarrier are to be introduced, and choosing an efficient signaling scheme for higher data rate. Hence, it has become crucial to incorporate the recent technical advances in the physical layer into the future wireless systems.

WLAN and Worldwide Interoperability for Microwave Access (WiMAX) are currently popular for data communication technique. As number of users and demand for higher data rate increases, these technologies should provide higher data rate and large band width to users for data and multimedia communication. Under these scenarios OFDM became an feasible option. A number of wired and wireless standards have adopted OFDM as a modulation standard for a variety of applications. For example, OFDM is the basis for the global standard for asymmetric digital subscriber line (ADSL) [1] and for digital audio broadcasting (DAB) [2], Digital Video Broadcasting (DVB) [3] to name a few. OFDM has been the modulation standard for IEEE 802.11a/ n/ ac and HiperLAN/2. Furthermore, OFDM has been adopted in the Wi-Fi arena where the standards like 802.11a, 802.11n, 802.11ac and more. It has also been chosen for new generation cellular telecommunications standard LTE / LTE-A. In addition to this, it is also being considered as the standard modulation for 5G communication [4] and Internet of Things (IOT) [5,6].

1.2.1 Advantage and disadvantage of OFDM system

OFDM is a modulation technique comprised of high data capacity and resilience to interference. These factors are highly essential in todays's high capacity communications scene. Moreover, orthogonality is the basic principle of the OFDM system. Any deviation or loss of orthogonality will deteriorate the OFDM system performance.

1.2.1.1 OFDM advantages

OFDM has been used in many high data rate wireless systems because numerous advantages it possesses. Some of the advantages include

- **Immunity to selective fading:** OFDM is more resistant to frequency selective fading than single carrier systems because it divides the overall channel into multiple narrow-band channels. These channels being narrowband suffer from flat fading and appear robust than wide-band channel

- **Resilience to interference:** Interference appearing on a channel may be bandwidth limited and in this way it does not affect all the sub-channels. This reduces the channel fluctuation.

- **Spectrum efficiency:** Use of closely-spaced overlapping orthogonal sub-carriers enables data transmission with low bandwidth channels and hence it makes efficient use of the available spectrum.

- **Resilient to ISI:** OFDM is very resilient to inter-symbol and inter-frame interference. This is due to the fact that each of the sub-channel carries low data rate data stream.

- **Resilient to narrow-band effects:** Use of adequate channel coding and interleaving make it possible to recover symbols lost due to the frequency selectivity of the channel and narrow band interference.

- **Simpler channel equalization:** In conventional digital communication and spread spectrum communication channel equalization has to be applied across the whole channel bandwidth. So channel equalization complexity increases. In contrast, only a one tap equalizer is required for OFDM channel equalization as it uses multiple sub-channels. This reduces equalization complexity in OFDM .

1.2.1.2 OFDM disadvantages

Whilst OFDM has been widely used, there are still a few disadvantages which need to be addressed when considering its use.

- **Sensitive to carrier offset and drift:** OFDM is sensitive to carrier frequency offset and drift compared to single carrier system
- **High peak to average power ratio:** OFDM signals are characterized by noise like amplitude variation in time domain and have relatively large dynamic range leading to high peak to average power ratio (PAPR). This impacts the RF amplifier efficiency as the amplifiers need to be linear and accommodate the large amplitude swings and these factors mean the amplifier cannot operate with a higher efficiency level.
- **Receiver complexity:** Complexity of the OFDM receiver increases with higher number of sub-channels.
- **Computational complexity demand:** Computational complexity associated with OFDM system increases both at transmitter and receiver by increasing the sub-carrier.

1.3 Research directions in OFDM system

OFDM transmission technology is an effective implementation of a multicarrier modulation principle where a high-speed serial data stream is split into multiple parallel low-rate streams, each modulating a different sub-carrier. This principle changes the frequency selective broadband channel to a multitude of flat narrowband channels. Additionally, this enables the channel to be be robust against multi-path propagation. Furthermore, OFDM can be easily combined with multiple antenna techniques leading to Multiple Input Multiple Output (MIMO). Due to the excellent performance, high flexibility, and simple implementation, OFDM has been the basis of a number of recent communication standards. Particularly since the network's interference becomes a driving factor for system performance, hence, it is a hot research topic.

Some of the research directions in OFDM and its ancillaries include

1. **PAPR reduction:** The use of a large number of sub-carriers introduces a high PAPR in OFDM systems. High PAPR limits the operation of transmitter power amplifier and causes saturation of receiver amplifier.

2. **Channel estimation:** Removal of interference is the key issue in any communication receiver. In OFDM systems channel estimation is an essential component towards interference mitigation.

3. **Frequency offset and drift:**OFDM signals at receiver are affected by frequency offset and drift due to relative motion between transmitter and receiver. The receiver in process of detection should mitigate these effects. Any frequency offset and drift in either the transmitter or receiver results in loss of the orthogonality.

4. **Application of OFDM to MIMO systems:** Though OFDM offers high speed data communication still its capacity is not increased. On the other hand MIMO's capability to achieve diversity gain can be exploited to achieve high capacity. So, combination of MIMO with OFDM will result in high speed high capacity communication system.

5. **Long Term Evolution (LTE):** LTE is now in evolving stage. Main objective of this project is to increase the capacity and speed of the network by digital signal processing techniques. Iterative channel estimation, traffic scheduling are few of the areas in which research is being carried out [7,8].

6. **Device to device (D2D) communication:** In this technology, cellular network users communicate with reduced interference of base station. Collision

avoidance communication, amplify-forward relaying are few area of research interest [9,10].

7. **Machine to machine (M2M) communication:** In this technology two machies of same type communicate each other by either wired network or wireless network [11].

8. **Inter Carrier Interference (ICI) canellation**. Loss of orthogonality among sub-carriers produces inter-carrier interference. Parallel interference cancellation, successive interference cancellation, ICI self cancellation with windowing are few techniques used for ICI cancellation [12].

9. VLSI and DSP implementation of OFDM Now a days VLSI and DSP implementation of different algorithms with low power consumption for OFDM is a challenging area research [13,14].

1.4 Literatures on different research fields

OFDM has been the most researched topic in last two decades. Many problem areas have been researched. However, in this thesis we will confine our topic to channel estimation, PAPR reduction, and use of MIMO and SDMA in OFDM.

1.4.1 Channnel estimation in OFDM systems

Recovery of the the transmitted data requires estimate of the Channel State Information (CSI). At the receiver side, CSI is obtained by employing different estimation techniques. Few of the standard technique adopted for channel estimation are Least Square (LS) [15], Minimum Mean Square Estimation (MMSE) [15], Bayesian Linear Unbiased Estimation (BLUE) etc.

In parlance with OFDM, usually pilot symbols are used to enable estimation of the channel. LS and MMSE based channel estimation were proposed in [16–19]. The mean square error estimation (MSE) in LS is more susceptible to noise when the channel is in deep fading. However, the simplicity of LS leverage its wide application. Incorporation of a weight matrix to LS can ultimately result in MMSE there by improving the performance of OFDM system. Increase in number of sub-carrier reduces fading but lead to computationally extensive MMSE. It is generally seen that MMSE is better than LS at the expense of higher computational complexity. Under the assumption of flat fading and slow fading, decision directed channel estimation (DDCE) can perform better [20–22]. DDCE uses the detected symbol feedback to track the channel variation. Performance of DDCE method depends on the fidelity of last detected symbol. Any deviation leads to propagate the error to subsequent estimation and the performance degrades. Moreover, performance degradation in fast fading scenario is more prevalent. Under fast fading environment, there is loss of orthogonality in OFDM systems. Deliberate loss of orthogonality leads inter carrier interference (ICI). The effects if ICI restricts the use of conventional one tap equalizer. Compensating the effects of ICI requires accurate estimation of channel frequency response. Though many researches have been carried out, most of them are derived under limited channel condition [23–26]. Maximum Likelihood (ML) [27] estimation and Expectation maximization (EM) [27] techniques are two very popular researched algorithms in this regard. Both of the methods possess their respective pros and cons. ML is optimum at the expense of computational complexity. EM algorithm uses lower order computation, but its computational complexity increases exponentially with increase in number of transmitted signal (subcarrier). Moreover, it is also seen that EM algorithm is generally not suitable for time varying channel [27]. Channel estimators based on Gaussian noise suffer from inferior estimation performance in presence of interference.To eradicate inferior estimation performance, Bhatia *et al.* [28,29] proposed a non-parametric maximum likelihood (NPML) estimator and detector for OFDM system in presence of interference .

1.4.2 PAPR Reduction

In the process of data transmission, signal after modulation is amplified in transmitter. This demands transmitter to operate in linear region, conversely, amplitude of data should lie in linear range of transmitter power amplifier. Also, communication system's performance heavily depends on the faithful amplification of transmitter power amplifier. The transmitter power amplifiers are high power amplifier used to transmit the signal. At any point of time, if the input power of the signal crosses the operation range then it will be going to non-linear range resulting in non-linear amplification including out of band radiation. Non-linearly amplified signal can not be easily retrieved in the receiver. Quantitatively, the ratio of peak power to the average power of a transmitter should be maintained low for faithful amplification. Furthermore, the reduction in PAPR results in a system that can either transmit more bits per second with the same hardware, or transmit the same bits per second with lower-power hardware (and therefore lower electricity costs [30]) (and therefore less expensive hardware), or both. To mitigate this effect many methods have been investigated. Few of the techniques involve clipping, clipping and filtering, coding and scrambling. A brief performance comparison of these techniques are summarised in Table. 1.1. Peak windowing, peak

Table 1.1: Performance comparison table of different PAPR reduction method

Method	Distortion	Bandwidth Efficiency	Complexity	Example
Clipping	In band and out of band	No effect	Simple	Clipping
Filtering	Yes	No effect	simple	Clipping and filtering
Coding	No	No effect	Huge	Hadamard Code
Scrambling	No	Decreases	Moderate, depends on method	PTS, SLM

cancellation technique and clipping are few examples of clipping method for PAPR reduction [31–33]. Use of orthogonal codes like Reed Muller code, Golay compementary sequence and Hadamard code for PAPR reduction have also been investigated [34–37].

Scrambling method, where the phase of OFDM symbol is changed before transmission has also been seen to be very effective [38–40].

1.4.3 MIMO and SDMA OFDM

Performance of OFDM in term of channel capacity has been further improved by employing MIMO [41]. Incorporation MIMO in OFDM substantially improves the channel capacity of communication system. Channel estimation, ICI cancellation and PAPR reduction, however, becomes difficult because of the extra complexity added by the channel. Use of Space Time Block Code (STBC) codes [42], proposed by Alamouti in US Patent 6185258 February 2001, somehow simplified the difficulties mentioned above. Space Division Multiple Access (SDMA) [43] is a special form of MIMO in which spatially separated users can use a single antenna for MIMO transmission. SDMA becomes challenging as different users access different antennas. In this scenario signal detection for individual user becomes important. This is solved by multi user detection schemes [44–46].

1.5 Motivational objectives

Preceding sections portrayed a juxtaposed scenario of different challenges in OFDM and MIMO systems. Considering the above challenges, each of the problem areas can be treated, independently. Hence, this thesis is mainly intended to improve the performance of the OFDM system by employing different signal processing algorithms for some of the problems in transmitter and receiver independently.

Firstly, the PAPR of OFDM transmitter should be minimised effectively. Though PTS and SLM techniques are optimum in to minimise the PAPR, their computational complexity very high and bandwidth efficiency is less. To overcome the computational complexity and bandwidth efficiency issue a different approach is required to reduce the

PAPR. This can be accomplished by design of an efficient method to reduce the PAPR in the transmitter including reduced complexity and better bandwidth efficiency.

Secondly, an efficient symbol recovery scheme; in-contrast to LS and MMSE where, noise and a priori information plays a pivotal role; can be employed at receiver. Use of pattern recognition algorithms for such type of situation can be investigated for efficacy of use.

Thirdly, space division multiple access (SDMA) enables multiple users to use the same bandwidth at different spatial locations. So, Multi User Detection (MUD) is essential in SDMA scenario. Detection in SDMA is done by MMSE. But the performance of MMSE not satisfactory. Hence, an SDMA MIMO OFDM based system bit detection can be more fine tuned with the advent of recent evolutionary meta heuristic computing algorithms.

1.6 Problem statement

Under the umbrella of above motivational objectives, work done in this thesis can be categorised into three directions. They are:

1. To conduct a rigorous analysis on channel estimation technique for OFDM based systems. Recovery of transmitted symbols requires channel state information at receiver. So estimate of channel is essential. Investigation of applicability of some recent pattern recognition algorithms like K-mean clustering, Hidden Markov model, Recurrent neural networks, Adaptive Boosting etc. suitable for OFDM system. Developing simulation environment for performance evaluation of Adaptive Boosting algorithm in OFDM receiver.
2. Understanding the mathematical formulation and implementation of conventional PAPR reduction methods like PTS and SLM. Investigate the scope of PAPR

improvement without loss of bandwidth along with lower computational complexity on the SISO OFDM receiver. Extending the investigation for plausible PAPR reduction in MIMO environment.

3. Analysis of formulation of multi user detection in MIMO OFDM scenario. Investigate the use of recent evolutionary algorithms like SDMA-MIMO-OFDM systems for multi user detection and to analyze the performance.

1.7 Thesis organisation

As discussed in earlier section this thesis analyses three aspects of a wireless communication system. In the transmitter side, it anlyses the PAPR of a communication system and proposes a new scheme for PAPR reduction. The proposed new PAPR reduction algorithm also extended to MIMO OFDM scenario. In the receiver side, this thesis analyses different existing channel estimation algorithms and proposes a recent pattern recognition algorithm for symbol recovery. Again, in the SDMA-MIMO-OFDM scenario it considers a new evolutionary algorithm for performance enhancement. Followed by this current chapter, the remaining of this thesis is organized as follows:

Chapter. 2 illustrates the basic working principle of a generic OFDM communication system. A detail mathematical representation of the OFDM system is also presented.

Chapter. 3 presents detail study of LS and MMSE based channel estimation algorithms. Mathematical analysis of LS and MMSE is carried out. Adaptive Boosting, a recent pattern recognition algorithm, has been analyzed for symbol recovery. Finally, performance of AdaBoost is compared with other algorithms.

Chapter. 4 depicts a detail study of different PAPR reduction methods. A mathematical study of PTS and SLM are presented. A Successive Addition Subtraction (SAS) preprocess is presented with its mathematical formulation. Performance measure of the proposed algorithm is analyzed. Furthermore, application of proposed algorithm is extended to MIMO OFDM systems. Alamouti's STBC code for different scenario of MIMO system is discussed. Finally, proposed SAS method is employed to carry out the PAPR reduction and performance of SAS under MIMO is presented.

Chapter. 5 elaborates the multi user detection scheme in space division multiple access (SDMA) scenario with its mathematical foundations. A detail study of Bat algorithm is outlined. Performance of SDMA-MIMO-OFDM employing Bat algorithm is evaluated. The performance of proposed algorithm is is compared with Genetic Algorithm and MMSE based receiver.

Chapter. 6 deciphers the conclusion and delineates the over all contribution of this thesis. Achievements and limitations of this thesis are discussed. An analysis of further research work is also presented.

1.8 Summary

A brief discussion on some of the earlier works related Orthogonal OFDM was presented.. The OFDM system, its working principle, pros and cons of OFDM system were discussed. The challenging research areas along with motivation for this thesis were depicted and the work flow of this dissertation is summarized.

2

OFDM systems: Concepts and challenges

"Man needs his difficulties because they are necessary to enjoy success."

A. P. J. Abdul Kalam

Contents

2.1 Introduction

Orthogonal Frequency Division Multiplexing (OFDM) is a multi-carrier communication system. OFDM extends the concept of single sub-carrier modulation by using parallel multiple sub-carriers within a channel. It uses a large number of closely separated orthogonal sub-carriers that are transmitted in parallel. Each of the sub-carrier is modulated with any conventional digital modulation scheme (such as QPSK, 16QAM, etc.) at low symbol rate. The combination of all sub-carriers enables data rates equivalent to conventional single-carrier modulation schemes. Thus OFDM can be considered as similar to the Frequency Division Multiplexing (FDM). In FDM different streams of information are mapped onto separate parallel frequency channels. Each FDM channel is separated from the others by a frequency guard band to reduce the possible interference between adjacent channels.

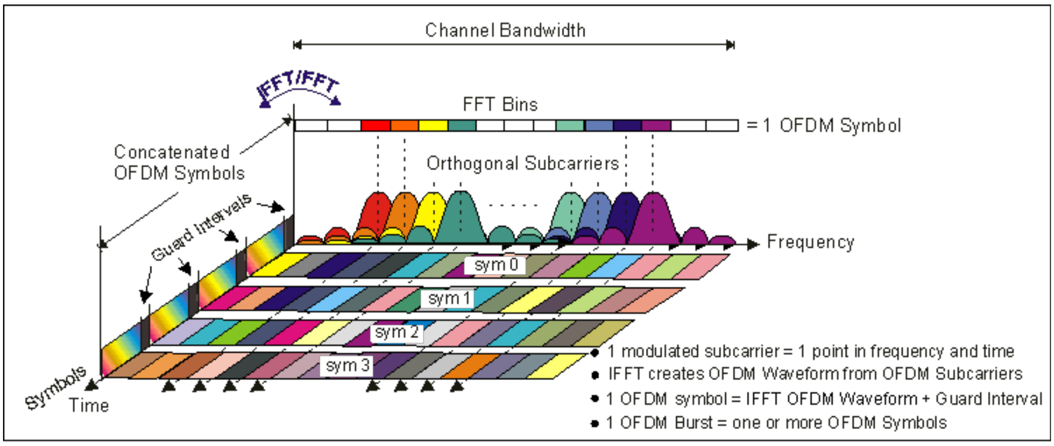
The OFDM scheme differs from the traditional FDM in following ways:

i. Multiple carriers carry single information stream

ii. Sub-carriers are orthogonal to each other

iii. A guard interval is added between adjacent symbols to minimize the channel delay spread and inter symbol interference (ISI).

Figure 2.1 shows the main concepts of an OFDM signal and the inter relationship between the frequency and time domains. The frequency axis contains N number of information carrying orthogonal sub-carriers. In the frequency domain, sub-carriers are independently modulated with complex data. Inverse FFT operation is performed on the frequency domain sub-carriers to produce the OFDM symbol in the time-domain. After IFFT operation, guard intervals are inserted to each symbols to prevent ISI at the receiver.Without ambiguity, it can be noted that ISI is caused by multi-path delay spread in the radio channel. At the receiver FFT operation is carried out on the OFDM symbols to recover the original transmit data bits.



Frequency-Time Representative of an OFDM signal

Figure 2.1: Frequency and time representation of OFDM spectrum. Reproduced from http://rfmw.em.keysight.com

Figure 2.2 shows the block diagram of an OFDM communication system. In the transmitter binary data from a data source coded inside the channel coding block. Channel coded serial data are then converted from serial data to parallel data. These parallel data are then mapped to multi amplitude multi phase modulation schemes (like QPSK, QAM4 etc.) in the symbol mapping block. Modulated parallel symbols are then converted to time domain signal through IFFT block. A guard interval signal equivalent to maximum channel delay is appended in the time domain signal to avoid inters symbol interference. The parallel data is then converted to serial data by converting them from digital to analog signal through DAC block. The analog signal is then transmitted through the transmitter antenna.

In the receiver side the signal is received and carrier synchronization carried out by carrier synchronizer. These signal are the converted back to digital data through through DAC converter. Guard removal and time synchronization is carried out by guard removal block and time synchronizer block respectively. The signal is transformed from time domain to frequency domain by FFT block. Channel estimation and subsequent symbol de-mapping is done through channel estimation block and symbol de-mapping block respectively. Parallel data are then converted to serial data through parallel to serial block. Finally bit decoding is carried out through decoding block.

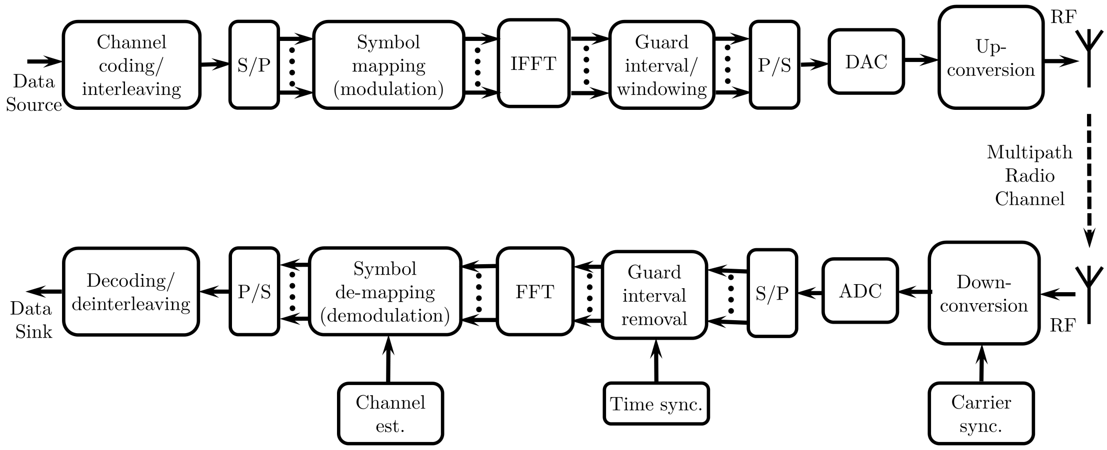


Figure 2.2: Block diagram of OFDM system.

2.2 Importance of Orthogonality

The OFDM signal can be viewed as a set of closely separated FDM sub-carriers. In the frequency domain, each transmitted sub-carrier results in a *sinc* function spectrum with side lobes that produce overlapping spectra between sub-carriers. This is presented in Figure.2.3. This results in sub-carrier interference except at orthogonally spaced frequencies. At orthogonal frequencies, the individual peaks of sub-carriers align with the nulls of all other sub-carriers. This overlap of spectral energy does not interfere with the system's ability to recover the original signal. The receiver multiplies the incoming signal by the known set of sinusoids to recover the original set of bits sent. The use of orthogonal sub-carriers facilitates large number of sub-carriers per bandwidth resulting in an increase in spectral efficiency. In a perfect OFDM signal, orthogonality prevents interference between overlapping carriers which is also known as Inter Carrier Interference (ICI). In OFDM systems, the sub-carriers interfere with each other only if there is a loss of orthogonality.

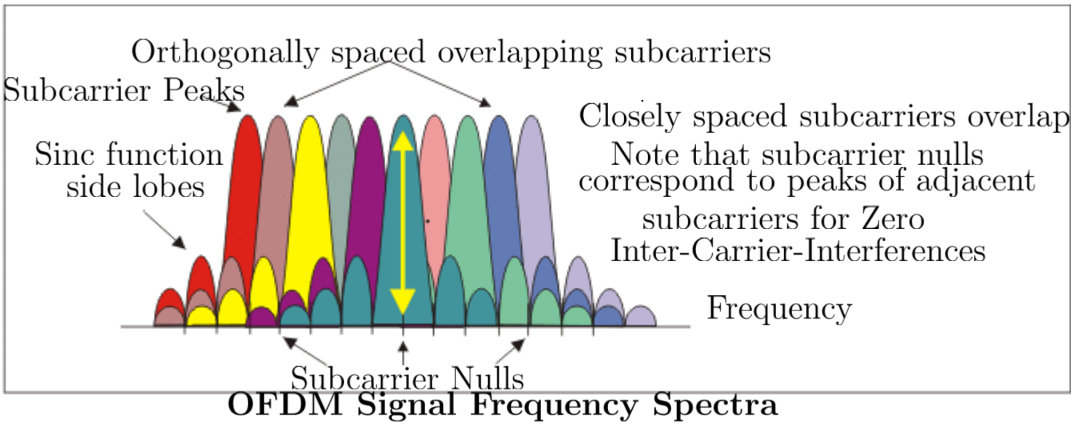


Figure 2.3: OFDM spectrum. Reproduced from http://rfmw.em.keysight.com

2.3 Mathematical description

If N sub-carriers are used, and each sub-carrier is modulated using $M-ary$ signalling, the OFDM symbol alphabet consists of one out of M^N number of combined symbols.

The low-pass equivalent OFDM signal can be represented as:

$$x(t) = \sum_{k=0}^{N-1} X_k e^{j2\pi kt/T_s}, \quad 0 \leq t < T_s$$

,

Where X_k are the data symbols, N is the number of sub-carriers, and T_s is the OFDM symbol time. The sub-carrier spacing of $\frac{1}{T_s}$ makes the symbols orthogonal over each symbol period; this property can be expressed as:

$$\frac{1}{T_s}\int_0^{T_s} \left(e^{j2\pi k_1 t/T_s}\right)^* \left(e^{j2\pi k_2 t/T_s}\right) dt \tag{2.1}$$

$$=\frac{1}{T_s}\int_0^{T_s} e^{j2\pi(k_2-k_1)t/T_s} dt = \delta_{k_1 k_2} \tag{2.2}$$

where $(\cdot)^*$ denotes the complex conjugate operator.

To avoid inter symbol interference in multipath fading channels, a guard interval of length T_g is inserted prior to the OFDM block. During this interval, a cyclic prefix is transmitted such that the signal in the interval $-T_g \leq t < 0$ equals the signal in the interval $(T_s - T_g) \leq t < T_s$. The OFDM signal with cyclic prefix can be presented as

$$x(t) = \sum_{k=0}^{N-1} X_k e^{j2\pi kt/T_s}, \quad -T_g \leq t < T_s$$

The above low-pass signal can be either real or complex-valued. Real-valued low-pass equivalent signals are typically transmitted at baseband—wireline applications such as DSL. For wireless applications, the low-pass signal is typically complex-valued; in which case, the transmitted signal is up-converted to a carrier frequency f_c. In general, the transmitted signal can be represented as:

$$s(t) = \Re\left\{x(t)e^{j2\pi f_c t}\right\} \tag{2.3}$$

$$= \sum_{k=0}^{N-1} |X_k| \cos\left(2\pi[f_c + k/T_s]t + \arg[X_k]\right) \tag{2.4}$$

$s(t)$ time domain signal to be transmitted. Sub-carrier separation by k/T_s ensures the orthogonality among sub-carriers.

2.4 OFDM variants

Several advantages and disadvantages of the OFDM system has been discussed in and . In this section several variants of OFDM is discussed.

There are several variants of OFDM used today. These follow the basic format for OFDM, but have additional attributes. Variations are introduced to provide specific advantages.

- **Coded OFDM:** Coded OFDM is a type of OFDM, where error correction coding is incorporated into the signal.

- **Flash OFDM:** It is a fast hopped form of OFDM. It uses multiple tones and fast hopping to spread signals over a given spectrum band.
- OFDMA: Orthogonal frequency division multiple access. A scheme used to provide a multiple access capability for applications such as cellular telecommunications while using OFDM technologies as modulation format.
- **Vector OFDM:** This form of OFDM uses the concept of MIMO technology. It is being developed by CISCO Systems. MIMO stands for Multiple Input Multiple output and it uses multiple antennas to transmit and receive the signals so that multi-path effects can be utilised to enhance the signal reception and improve the transmission data rates that can be supported.
- **Wideband OFDM:** It uses a degree of spacing between the channels that is large enough that any frequency errors between transmitter and receiver do not affect the performance. It is particularly applicable to Wi-Fi systems.

Each form of OFDM technique utilize the same basic concept of using close spaced orthogonal carriers each carrying low data rate signals.

3

Adaptive boosting based symbol recovery in OFDM systems

At their best, at their most creative, science and engineering are attributes of liberty—noble expressions of man's God-given right to investigate and explore the universe without fear of social or political or religious reprisals.

David Sarnoff

Contents

This chapter introduces the concept of binary boosting algorithm and multi class boosting algorithm. A multi class adaptive boosting algorithm was employed to estimate the receiver data symbol. LS and MMSE based system performance is also portrayed.

3.1 Introduction

Communication systems use Frequency Division Multiple Access (FDMA), Time Division multiple Access (TDMA) and Code Division Multiple Access (CDMA) for efficient spectrum sharing between users. FDMA suffers from low spectrum usage and TDMA system performance degrades due to multipath delay spread causing Inter Symbol Interference (ISI). In contrast, OFDM enables high data rate wireless applications in a multipath radio environment without the need for complex receivers. OFDM is a multi-channel modulation scheme employing Frequency Division Multiplexing (FDM) with orthogonal sub-carriers, each modulating a low bit-rate digital stream. OFDM uses N overlapping (but orthogonal) sub bands, each carrying a baud rate of $1/T_s$ and they are spaced $1/T_s$ Hz apart. Because of the selected frequency spacing, all the sub-carriers are mathematically orthogonal to each other. This permits proper demodulation of symbol streams without the requirement of non overlapping spectra.

Currently, OFDM is the most widely used technology as it combines the advantages of providing high data rates along with simple equalization hence better bandwidth efficiency. Advances in DSP and VLSI hardware software has made it feasible to implement complex receivers. With this OFDM has been adopted for many application standards including DAB, DVB, high speed modems over ADSL and WLAN IEEE 802.11a/b/g/n/ac to name a few.

The accuracy of channel state information estimated at receiver greatly influences the overall system performance [47] of OFDM. The main challenges associated with OFDM systems today are channel identification and tracking, channel coding and equalization. In wideband mobile channels, pilot-based signal correction schemes are employed [48]. Most channel estimation methods for OFDM transmission have been developed under the assumption of a slow fading channel, where the channel transfer function is assumed stationary within one OFDM data block. Additionally, the channel transfer function estimated in the previous OFDM data block is used as the channel transfer function for the current data block. Unfortunately, the channel transfer function of a wideband radio channel may have significant changes even within one OFDM data block. Therefore, it is preferable to estimate channel characteristic based on the pilot signals in each individual OFDM data block [49].

Recently, in an elegant channel estimation technique for OFDM mobile communication systems was proposed by Sohail *et al.* [50]. In this a semi-blind low complexity frequency domain channel estimation algorithm for multi-access OFDM systems was proposed. Many researchers have pursued channel estimation in the time domain. A joint carrier frequency synchronization and channel estimation scheme, using the expectation-maximization (EM) approach was presented by Lee *et al.* [51] while Hou *et al.* [52] proposed a subspace tracking method for OFDM. In [53], a joint channel channel and data estimation algorithm is presented which makes the collective use of data and channel constraints. A joint frequency-offset and channel estimation technique for multi-symbol encapsulated (MSE) system was proposed by [54], while the Liu *et al.* [55] presented a sequential method based on carrier frequency offset and symbol timing estimation for WLAN application. Qin *et al.* [56] estimated the channel based on power spectral density (PSD) and least squares (LS) estimation for OFDM systems affected by timing offsets. A pilot aided channel estimation algorithm in the presence of synchronous noise by exploiting the a priori available information about the interference structure was presented by Jeremic *et al.* [57], while [58] used implicit pilots for joint detection and channel estimation. A joint time domain tracking of channel frequency offset for OFDM systems was suggested by Roman *et al.* [59], while a time domain carrier frequency offset (CFO) tracking method based on Particle filtering was presented in [60].

In this work a multi-class adaptive boosting(AdaBoost) algorithm, pattern recognition algorithm is proposed by Zhu *et al.* [61] , has been used for transmitted symbol recovery at receiver through the pilot aided channel estimation. From a statistical prospective, AdaBoost can be viewed as a forward stepwise additive model using an exponential loss function for multi-class classification. Adaboost algorithm combines weak classifiers and only requires the performance of each weak classifier be better than random guessing.

Following this introduction remaining part of the chapter is arranged as follows: Section. 3.2 describes the mathematical model of OFDM systems and its channel model along with two types of pilot arrangement. The implementation of AdaBoost and other algorithms (like LS, MMSE, and BLUE) is discussed in Section. 3.3. Section. 3.4 describes the performance analysis of different algorithms and finally Section. 5 draws up the summary of the chapter.

3.2 System Description

A simplified block diagram of OFDM system with channel estimation is presented in Figure 2.2. In this chapter the system was considered to be perfect time synchronization and carrier synchronization. The block diagram for simulation of channel estimation is given in Figure 3.1. First binary information data are grouped and mapped into multi-amplitude-multi-phase signals. After pilot carrier and data carrier insertion, the

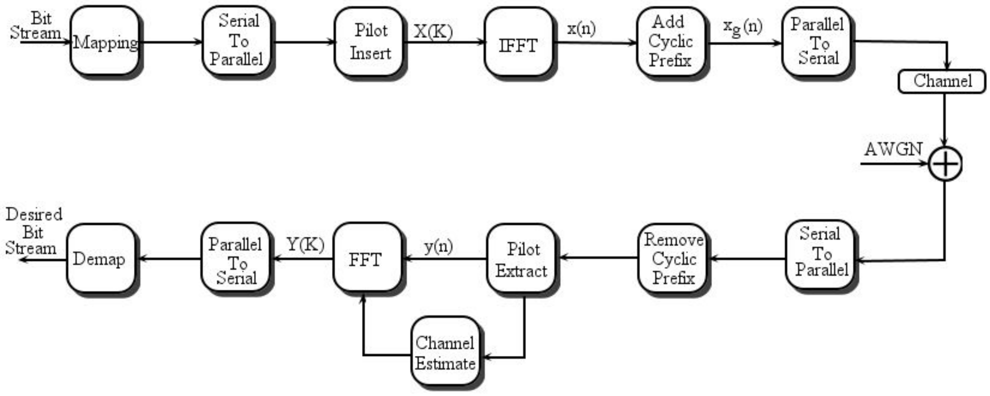


Figure 3.1: Base band simulation model of the OFDM system

modulated data $X(k)$ are sent to an IDFT block, and transformed and multiplexed into $x(n)$ as [50,53]

$$x(n) = IFFT\{X(k)\} = \sum_{k=0}^{N-1} X(k)e^{j2\pi kn/N} \quad for \;\; n = 0, 1, ..., N-1 \tag{3.1}$$

where N is the number of sub-carriers. The guard interval N_g is inserted to prevent inter-symbol interference in OFDM systems, and the resultant samples with guard band can be represented as $x_g(n)$. [50,53]

$$x_g(n) = \begin{cases} x(N+n) & n = N_g, N_g - 1, \ldots, -1 \\ x(n) & n = 0, 1, \ldots, N-1 \end{cases} \tag{3.2}$$

where N_g is the number of samples in the guard interval. The transmitted signal is then sent to the channel. The received signal can be represented by [50,53]

$$y_g(n) = x_g(n) \otimes h(n) \; + \; w(n) \tag{3.3}$$

Where $h(n)$ is the channel impulse response (CIR) and $w(n)$ is the Additive White Gaussian Noise (AWGN) and $\otimes$ is the circular convolution. Here we choose the channel to be Rayleigh fading channel. With this, the channel impulse response $h(n)$ can be expressed as [15,50,53]

$$h(n) = \sum_{i=0}^{r-1} h_i \; e^{(j2\pi f_{Di} T_s \frac{n}{N})} \delta(t - \tau_i) \tag{3.4}$$

Where r constitute the total number of propagation paths, h_i is the complex impulse response of the ith path, f_{Di} is the ith path's Doppler frequency shift which causes Inter Channel Interference (ICI) at the received signals and τ_i is the ith path delay time normalized by the sampling time. After removing the guard interval from $y_g(n)$, the received samples $y(n)$ are sent to a FFT block to demultiplex the multi-carrier signals.

$$Y(k) = FFT\{y(n)\} = \frac{1}{N}\sum_{n=0}^{N-1} y(n)e^{-j2\pi kn/N} \quad for\ k = 0, 1, \ldots, N-1 \tag{3.5}$$

In OFDM system a Cyclic Prefix (CP) is added either at the front or back of the OFDM symbol. CP length is preferably more or equal to maximum delay of the channel. This cyclic prefix can mitigate the inter symbol interference. If we assume that the guard interval is longer than the length of channel impulse response, no inter-symbol interference among OFDM symbols is seen and the demultiplexed samples $Y(k)$ can be then represented by

$$Y(k) = X(k)H(k) + W(k), \quad k = 0, 1, \ldots, N-1 \tag{3.6}$$

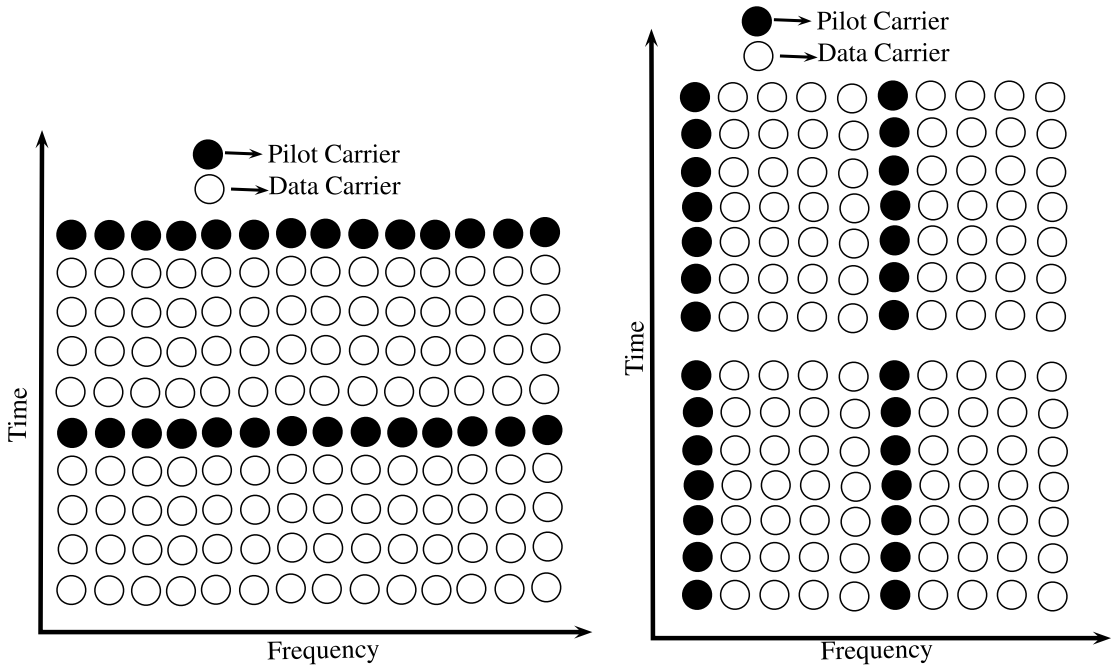
Where $H(k) = h_i\ e^{j2\pi f_{Di}T_s \frac{sin(\pi f_{Di}T_s)}{\pi f_{Di}T_s}}\ e^{-j\frac{2\pi\tau_i}{N}k}$ and $W(k)$ is the Fourier transform of the AWGN $w(k)$.

Following this, the received pilot signals $Y_p(k)$ are extracted from $Y(k)$. $Y_p(K)$ training symbols sent through sub-carriers. The channel with transfer function $H(k)$ can be obtained from the information carried by $H_p(k)$. With the knowledge of the channel responses $H(k)$, the transmitted data samples $X(k)$ can be recovered by simply dividing the received signal by the channel response:

$$\hat{X}(k) = \frac{Y(k)}{\hat{H}(k)} \tag{3.7}$$

where $\hat{H}(k)$ is an estimate of $H(k)$. After signal de-mapping, the source binary information data are reconstructed at the receiver output.

The OFDM transmission scheme makes it easy to assign pilots in both time and frequency domain. Figure.3.2 presents two popular types of pilot arrangement. The first kind of pilot arrangement shown in Figure.3.2a is denoted as block-type pilot



(a) Block Type **(b)** Comb Type

Figure 3.2: Pilot Arrangements

arrangement, where the pilot signal is assigned to a particular OFDM block, which is sent periodically in time domain. This type of pilot arrangement is especially suitable for slow-fading radio channels. The estimation of channel response is usually obtained by either LS or MMSE estimates of training pilots [51].

The second kind of pilot arrangement, shown in Figure. 3.2b, is termed comb-type pilot arrangement. The pilot signals are uniformly distributed within each OFDM block. Assuming that the payloads of pilot signals of the two arrangements are the same, the comb-type pilot assignment has a higher retransmission rate. Thus, the comb-type pilot arrangement system provides better resistance to fast-fading channels. Since only some sub-carriers contain the pilot signal, the channel response of nonpilot subcarriers will be estimated by interpolating neighbouring pilot sub-channels. Thus, the comb-type pilot arrangement is sensitive to frequency selectivity compared to the block-type pilot arrangement system. That is, the pilot spacing $(\Delta f)_p$, must be much smaller than the coherence bandwidth of the channel $(\Delta f)_c$ [49].

3.3 Channel Estimation

In the fast fading environment comb type pilot arrangement provides better performance as compared to block type pilot arrangement. In case of comb type pilot arrangement, pilot carriers are uniformly placed as to track the channel variations in fast fading environment. Moreover, pilots that carry information or data can also be estimated by interpolation techniques. For comb-type pilot sub-carrier arrangement, the N_p pilot signals $X_p(m),\quad m = 0, 1, ..., N_p - 1$, are uniformly inserted into $X(k)$. That is, the total N sub-carriers are divided into N_p groups, each with $L = N/N_p$ adjacent sub-carriers. In each group, the first sub-carrier is used to transmit pilot signal. The OFDM signal modulated on the kth sub-carrier can be expressed as [62]

$$\begin{aligned} X(k) &= X(mL + l) \\ &= \begin{cases} X_p(m), & l = 0, \\ X(k), & l = 1, 2, \ldots, L-1 \end{cases} \end{aligned} \tag{3.8}$$

Where X_p is the pilot information. Let

$$\begin{aligned} H_P &= [H_p(0)\ H_p(1)\ \ldots H_p(N_p - 1)]^T \\ &= [H(0)\ H(L-1)\ \ldots H((N_p - 1)(L-1))]^T \end{aligned} \tag{3.9}$$

be the channel response of pilot carriers, and

$$Y_p = [Y_p(0)\ Y_p(1) \ldots Y_p(N_p - 1)] \tag{3.10}$$

be a vector of received pilot signals. The received pilot signal vector Y_p can be expressed as

$$Y_p = X_p H_p + W_p \tag{3.11}$$

where

$$X_p = \begin{bmatrix} X_p(0) & 0 & \dots & 0 \\ \vdots & X_p(1) & \dots & \vdots \\ 0 & 0 & \dots & X_p(N_p-1) \end{bmatrix}$$

where W_p is the vector of Gaussian noise in pilot sub-carriers.

3.3.1 LS Estimation

In conventional comb-type pilot based channel estimation methods, the estimation of pilot signals, is based on the LS method and can be presented as [62]

$$\begin{aligned} \hat{H}_{p,ls} &= [H_{p,ls}(0)\ H_{p,ls}(1)\ \dots\ H_{p,ls}(N_p-1)] \\ &= X_p^{-1} Y_p \\ &= [\tfrac{Y_p(0)}{X_p(0)}\ \tfrac{Y_p(1)}{X_p(1)}\ \dots\ \tfrac{Y_p(N_p-1)}{X_p(N_p-1)}] \end{aligned} \tag{3.12}$$

The LS estimate of H_p is susceptible to AWGN and Inter-Carrier Interference (ICI). Because the channel responses of data subcarriers are obtained by interpolating the channel characterstics of pilot subcarriers, the performance of OFDM systems based on comb-type pilot arrangement is highly dependent on the rigorousness of estimate of pilot signals. Thus, an estimate with better performance than the LS estimate is required. The MMSE estimate has been seen to perform better than the LS estimate for channel estimation in OFDM systems based on block-type pilot arrangement [27]. The Mean Square Error (MSE) is an important criteria for any estimation. Beek *et al.* [15] claimed that MMSE estimate has about 10-15 dB gain in SNR over the LS estimate for desired MSE value. Major drawback of the MMSE estimate is its high complexity, which grows exponentially with the observation samples.

3.3.2 MMSE Estimation

The MMSE estimator employs the second order statistics of the channel conditions in order to minimises Mean Square Error (MSE). Let $\underline{R}_{hh}$, $\underline{R}_{HH}$, and $\underline{R}_{YY}$ be the auto-covariance matrix of h, H, and Y, respectively and $\underline{R}_{hY}$ be the cross covariance matrix between h and Y. Also, $\sigma_w^2 = E\{|w^2|\}$ denotes the variance of AWGN. Assuming that the channel vector h, and the AWGN w are uncorrelated, it can be shown that [62]

$$\underline{R}_{HH} = E\{HH^H\} = E\{(\underline{F}h)(\underline{F}h)^H\} = \underline{F}\ \underline{R}_{hh}\underline{F}^H \tag{3.13}$$

where

$$\underline{F} = \begin{bmatrix} TW_N^{00} & \dots & TW_N^{0(N-1)} \\ \vdots & \ddots & \vdots \\ TW_N^{(N-1)0} & \dots & TW_N^{(N-1)(N-1)} \end{bmatrix} \tag{3.14}$$

and $TW_N^{i,k} = \frac{1}{\sqrt{N}} e^{-j2\pi i \frac{k}{N}}$ is called as the twidle factor matrix. Assuming $\underline{R}_{hh}$ (thus $\underline{R}_{HH}$) and σ_w^2 are known at the receiver in advance, the MMSE estimator of the h is given by $\hat{h}_{MMSE} = \underline{R}_{hY}\underline{R}_{YY}YY^H$. Finally it can be estimated that

$$\begin{aligned} \hat{H}_{MMSE} &= \underline{F}\hat{h}_{MMSE} \\ &= \underline{R}_{HH}[\underline{R}_{HH} + \sigma_w^2(XX^{Ht})^{-1}]^{-1}\hat{H}_{LS} \end{aligned} \tag{3.15}$$

MMSE employs the second order statistics of the channel for estimation. Some times the channel statistics are not available, so it is difficult to estimate the channel. However, in OFDM systems the pilot carrier symbols are available at the receiver to aid the receiver tuning.

3.3.3 Best Linear Unbiased Estimation

This theorem is termed as Gauss-Markov Theorem. If we restrict the estimator to be linear in data and find the linear estimator that is unbiased and minimum variance then the estimator is called Best Linear Unbiased Estimator (BLUE). BLUE can be determined with knowledge of only the first and second moment of the PDF. Since complete knowledge of the PDF is not necessary, BLUE can be a recommended technique for practical implementation [63]. BLUE can be stated under

Gauss-Markov Theorem: If the data can be modeled in the following linear form

$$Y = XH + W \tag{3.16}$$

where X is a known $N \times p$ matrix and H is a $p \times 1$ vector of parameters to be estimated, and W is a $N \times 1$ noise vector with zero mean and covariance C (the PDF of W is otherwise arbitrary), then BLUE of H is given by

$$H_{BLUE} = (H^* C^{-1} H)^{-1} H^* C^{-1} X \tag{3.17}$$

H^* is the conjugate transpose or Hermitian Transpose.

3.4 AdaBoost

Boosting is a general technique used to improve the accuracy of any given learning algorithm. AdaBoost was originally defined for two class problems but it can be extended for multi-class and regression problems [61,64]. The AdaBoost algorithm, introduced in 1995 by Freund and Schapire, has been used to solve many of the practical problems of the earlier boosting algorithms [64]. The AdaBoost algorithm for multi-class problem is discussed below.

Suppose we are given a set of training data (x_1, c_1), (x_2, c_2), $\ldots$, (x_n, c_n), where the input (prediction variable) $x_i \in \mathbb{R}^p$ and the output (response variable) c_i is quantitative values in a finite set, e.g $1, 2, \ldots, K$. Where K is the number of classes. Usually it is assumed that the training data are composed from independently and identically distributed (iid) samples from an unknown probability distribution $Prob(X, C)$. The goal is to find out a classification rule $C(x)$ from the training data, so that when given a new input x, it can be assigned a class label c from $1, 2, \ldots, K$. The misclassification error rate of a classifier $C(x)$ is given by $1 - \sum_{k=1}^{K} E_X[\mathbb{I}_{C(X)=k}\ Prob(C = k|X)]$. So

$$C^{\star}(x) = arg\ \max_k\ Prob(C = k|X = x) \tag{3.18}$$

will minimize this quantity with the misclassification error rate equal to

$$1\ -\ E_X\ \max_k\ Prob(C = k|X)$$

. This classifier is known as *Bayes Classifier* and the error rate is defined as *Bayes Error Rate*. Bayes classifier has been widely used in communication systems as a classifier and provides maximum a-posterior probability performance index. The multiclass AdaBoost algorithm tries to approximate the Bayes Classifier $C^{\star}(x)$ by combining many weak classifiers. Starting with an unweighted training sample, the AdaBoost builds a classifier that produces class of labels. If a training data point is misclassified, the weight of that training data point is increased (boosted). A second classifier is built using these new weights, which are no longer equal. Again, misclassified training data have their weights boosted and the procedure is repeated. Typically, 500 to 1000 classifiers can be built this way. A score is assigned to each classifier, and the final classifier is defined as the score weighted linear combination of the classifiers from each stage. Specifically, let $T(x)$ denote a weak multi-class classifier that assigns a class label to x, then the AdaBoost algorithm [61] proceeds as follows:

Multiclass AdaBoost Algorithm:

The Algorithm to imoliment AdaBoost can be implemented as under

1. Initialize the observation weights $w_i = 1/n,\ i = 1,\ 2,\ \ldots,\ n$.

2. For m = 1 to M:

   a) Fit a classifier $T^{(m)}(x)$ to the training data using weights w_i.

   b) Compute

   $$err^{(m)} = \sum_{i=1}^{n} w_i\, \mathbb{I}(c_i \neq T^{(m)}(x_i)) / \sum_{i=1}^{n} w_i$$

   c) Compute

   $$\alpha^{(m)} = \log \frac{1 - err^{(m)}}{err^{(m)}} + \log(K - 1)$$

   d) Set

   $$w_i \leftarrow w_i\, exp(\alpha^{(m)}.\, \mathbb{I}(c_i \neq T^{(m)}(x_i)))$$

   for i=1, 2, . . . , n.

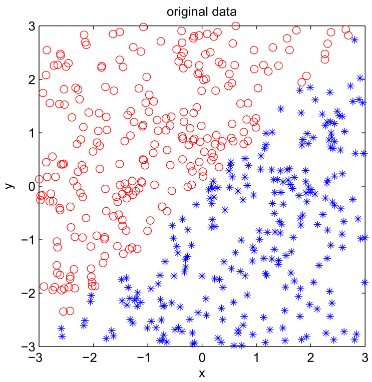
   e) Re-normalize w_i.

3. Output

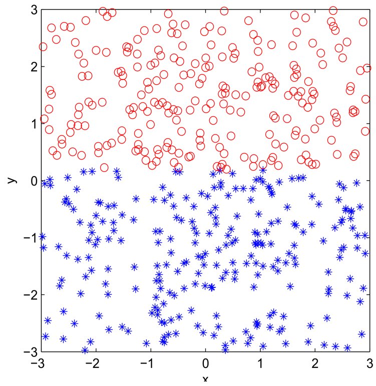
$$C(x) = arg \max_k \sum_{m=1}^{M} \alpha^{(m)}\, \mathbb{I}\, (T^{(m)}\, (x) = k)$$

3.4.1 Examples of Classification through AdaBoost Algorithm

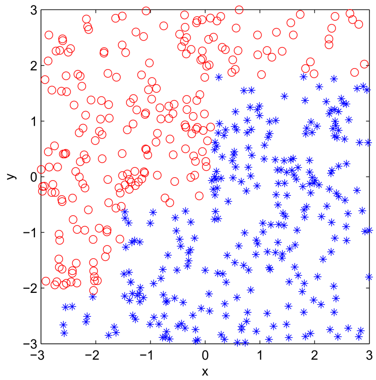
AdaBoost is widely used in classification applications. In this subsection we present two examples of classification to show the working of AdaBoost algorithm. First we consider a linearly separable classification problem and then a non-linearly separable classification problem.



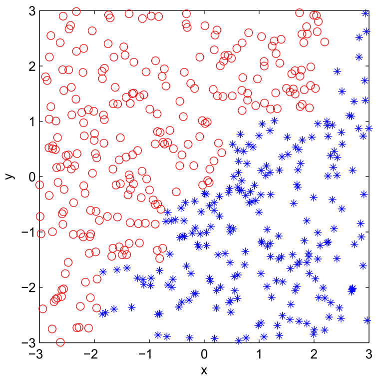
(a) Original data.



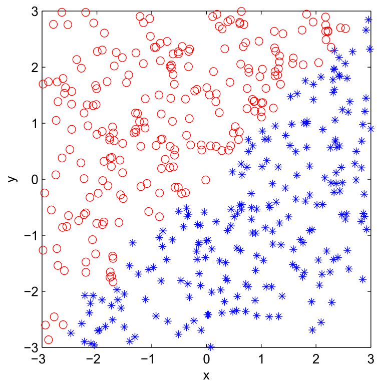
(b) Data classification by using M=2 number of classifiers.



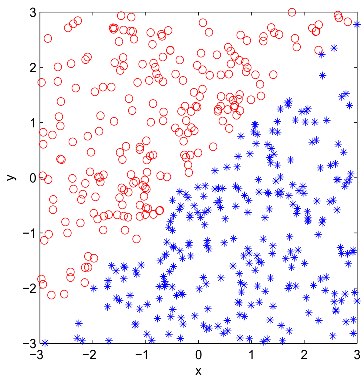
(c) Data classification by using M=5 number of classifiers.



(d) Data classification by using M=10 number of classifiers.



(e) Data classification by using M=25 number of classifiers.



(f) Data classification by using M=50 number of classifiers.

Figure 3.3: Two class linearly separable problem and its classification with different number of weak classifiers

Figure 3.3 represents a binary linearly separable problem. Circle mark in Red color represents on class of data and blue color star marks represents another set of data. The data is generated by the equation

$$z = \begin{cases} 1 & \text{if } x \leq y \\ -1 & \text{if } x > y \end{cases}$$

Where $z$is the value of the function, $x$and$y$ are two coordinates of a Cartesian system. If $z = 1$ it represents one class of data (blue star marks in Figure 3.3a) and and if $z = -1$ it represents another class of data (red circle marks in Figure 3.3a). These two classes of data were presented in Figure 3.3a. The input data set was subjected to

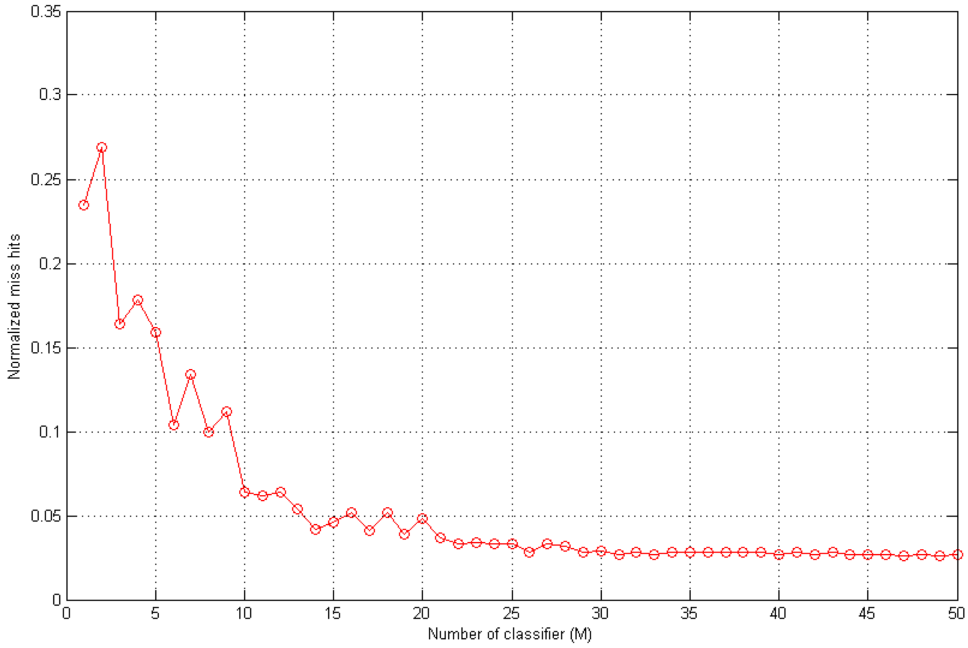


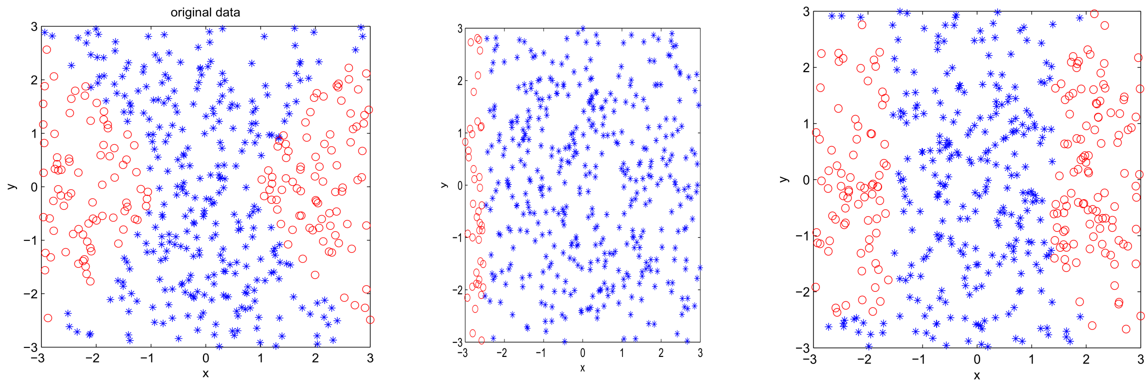
Figure 3.4: Linearly separable miss hit error during training

adaptive noise. The training of AdaBoost algorithm was carried out by employing M number of weak classifiers (in this case 50 weak classifiers). Figure 3.4 represents the normalized miss hit by increasing the number weak classifiers. When error is saturated by employing higher number weak classifiers the algorithm is terminated. Hitherto, the testing can be done. Figure 3.3b through Figure 3.3f represent the classified databy employing $M = 2,\ 5$ 10 25 and 50 number classifiers respectively. From these figures it is evident that data classification becomes more accurate as the number of classifiers increases. Similarly the same procedure was carried out for nonlinearly separable problem.

In the case of nonlinearly separable problem, two classes of data set were generated by

$$z = \begin{cases} 1 & \text{if } x^2 - y^2 \leq 1 \\ -1 & \text{if } x^2 - y^2 > 1 \end{cases}$$

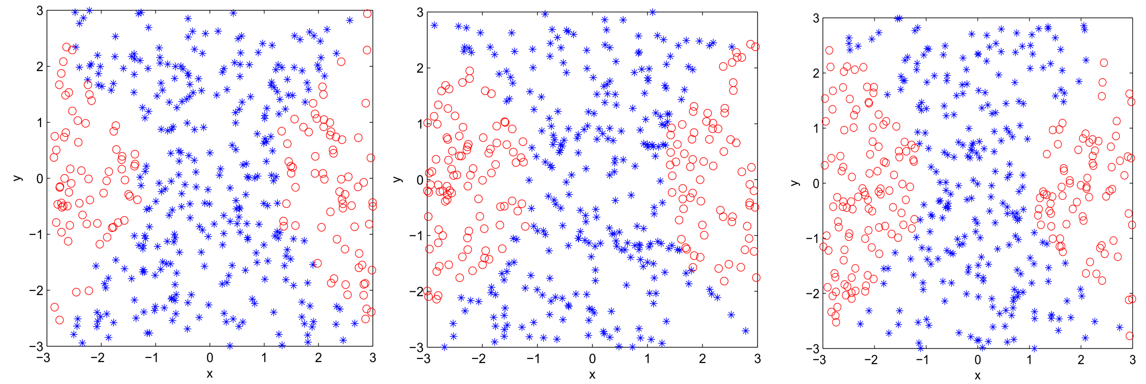
If $z = 1$ it represents one class of data and and if $z = -1$ it represents another class of data. These two classes of nonlinearly separable data were portrayed in Figure 3.5a.



(a) Original data.

(b) Data classification by using M=2 number of classifiers.

(c) Data classification by using M=5 number of classifiers.



(d) Data classification by using M=25 number of classifiers.

(e) Data classification by using M=50 number of classifiers.

(f) Data classification by using M=100 number of classifiers.

Figure 3.5: Two class nonlinearly separable problem and its classification with different number of weak classifiers

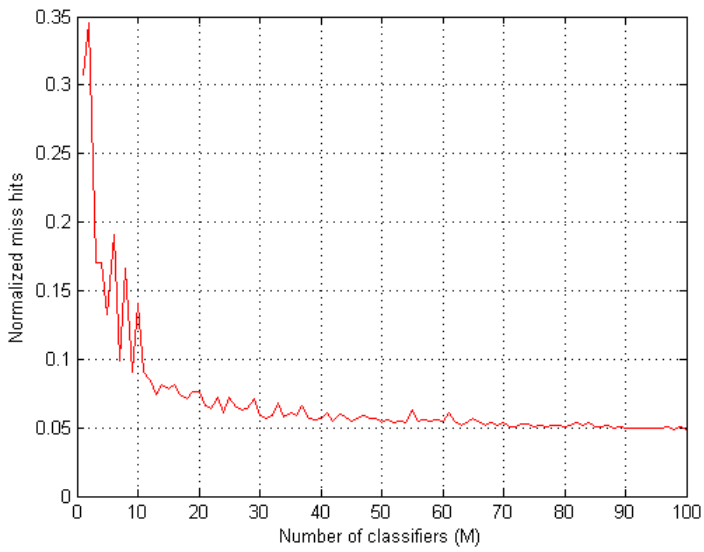


Figure 3.6: Nonlinearly separable miss hit error during training

Blue stars correspond to $z = 1$ and red circles correspond to $z = -1$. In this case $M = 100$ number of classifiers were used for proper classification. The normalized mis hit versus number of classifiers curve is given in Figure 3.6. After training is over, the clssified data were presented in Figure 3.5b to 3.5f using 2, 5, 25, 50 and 100 number of classifiers respectively.

3.5 AdaBoost based symbol recovery in OFDM systems

AdaBoost has been very popular in pattern recognition and classification applications. In this thesis, the author proposed to use AdaBoost for recovery of transmitted symbol at the receiver through pilot aided channel estimation. Channel estimation can be made by any of the methods mentioned above. However, LS algorithm is more popular and easily implementable for its simplicity and low computational complexity. However, when the signal power is low compared to noise power symbol error rate (SER) performance using LS channel estimation deteriorates drastically. To further improve the SER performance specially in low SNR values AdaBoost based symbol recovery was applied at the receiver. In the training phase of AdaBoost, a training data set was generated. Suppose we are using a $M - ary$ constellation. One constellation over all sub-carriers is received at the receiver. Like wise M number of transmission are made for M constellations. LS based channel estimation was carried out at the receiver. The recovered symbols, still contaminated with some noise, through LS estimation are now trained with AdaBoost the algorithm for better symbol recovery. Once training phase is completed, data transmission was carried out as usual. Each time symbols recovered through LS estimation were passed through the AdaBoost for fine tuning of parameters.

Table 3.1: OFDM Parameters

No of Subcarriers	256
No. of Pilot Carriers	32
Guard Interval	64
Guard Type	Cyclic Extension

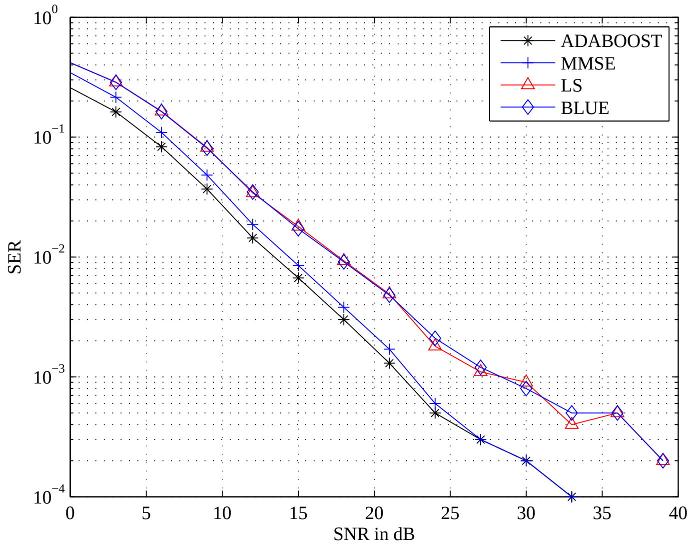


Figure 3.7: Performance Comparison of Different Algorithms

3.6 Simulation Results

To evaluate the performance of proposed AdaBoost based symbol recovery technique simulations were carried out with different channel conditions. In first simulation, a Rayleigh fading channel was considered with 5 paths and the Doppler frequency shift of 50 Hz. The OFDM system channel estimation was simulated with LS, MMSE, BLUE and AdaBoost techniques. In all simulations, QAM-16 was used as the modulation scheme. Other parameters of the simulation are presented in the Table.3.1. Figure.3.7 shows comparison of Symbol Error Rate (SER) for LS, MMSE, BLUE and AdaBoost based techniques. Figure.3.7 shows that the AdaBoost algorithm improves the performance specially in low SNR condition. However, at high SNR both MMSE and AdaBoost show a similar performance. Furthermore, AdaBoost shows better performance when compared to LS and BLUE. Nevertheless, BLUE and LS perform similar with BLUE providing marginal improvement to LS. As BLUE has almost same performance as LS, in subsequent simulations, simulations were confined to LS estimation only. In order to further verify the performance of AdaBoost based symbol recovery two more channels were considered. One channel was with line of sight component and other without line of sight component. In both of the simulation 512 sub-carriers were employed. The performances of of AdaBoost for line of sight and non line of sight channels are presented in Figure 3.8 and 3.9 respectively. In all the cases it is observed that the performance AdaBoost is much simpler than LS algorithm and slightly better than MMSE algorithm. Specially in low SNR region the performance improvement is better. A quantitative analysis of SNR gain at SER=10^{-3} for all the three channels are given in Table 3.2. From the Table 3.2, it is seen that

Table 3.2: Quantitative performance analysis of different algorithms

Methods	channel		
	Line of sight	Non-line of sight	Raleyigh
LS	21.3	23.0	28.4
MMSE	16.8	17.6	22.5
AdaBoost	16.7	16.8	21.8

proposed Adaboost based symbol recovery has a SNR gain of 4.5dB, while MMSE has 4.4dB SNR gain over LS algorithm in line of sight scenario. In the non line of sight scenario, AdaBoost has a SNR gain of 6.1 dB over LS and MMSE has 5.3 dB gain over LS algorithm. For Rayleigh channel AdaBoost attained a gain of 6.6 dB and MMSE has 5.8 dB gain over LS algorithm. However, the gain of AdaBoost over MMSE is confined with in 1 dB in all the cases.

Performance of the AdaBoost algorithm was also evaluated for the Rayleigh channels by varying the number of taps. Figure 3.10 to 3.12 shows the performance of different algorithm for 3, 5 and 7 tap channels respectively. From Figure 3.10 to 3.12 it is seen that both MMSE and AdaBoost algorithms outperform LS. At lower SNR, though, the performance of AdaBoost algorithm is better than MMSE, but at higher SNR

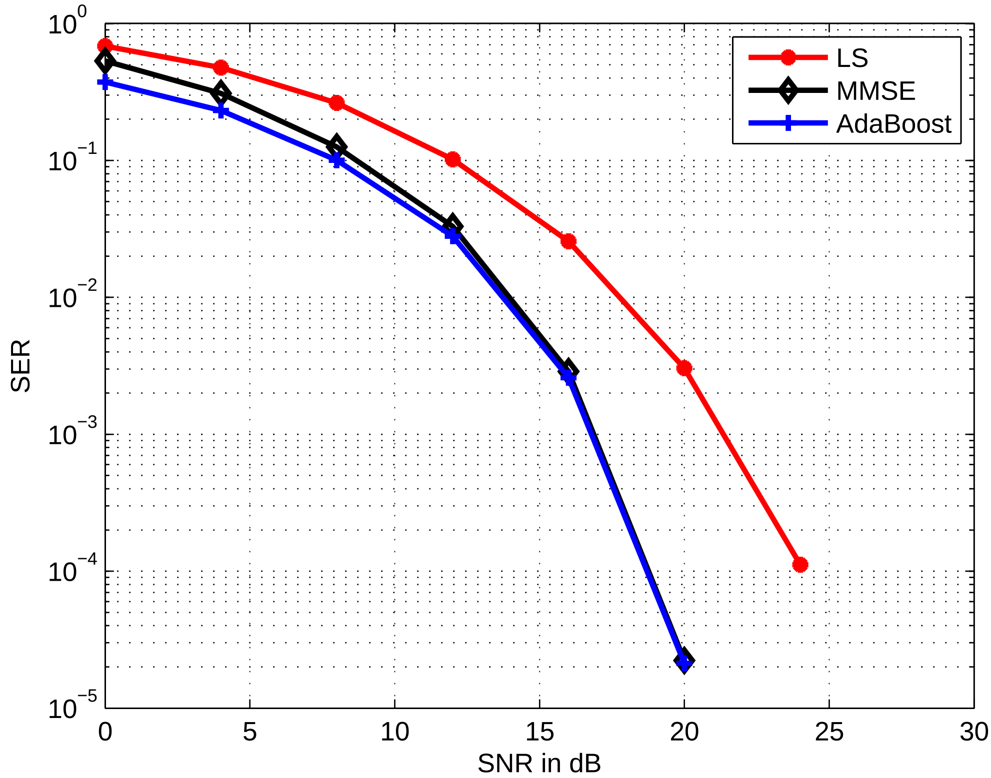


Figure 3.8: Performance comparison under line of sight channel [1 .5]

the BER performance is almost same. Again, the performance of LS, MMSE and AdaBoost degrades with increase in number of taps.

Performance of LS, MMSE and AdaBoost is also investigated under mobility scenario. Figure 3.13 to 3.16 present performances of these algorithms in mobility environment. Figure 3.13 presents performance of LS, MMSE and AdaBoost algorithm in system where an user travels 50 Kilometer per hour. Similarly, Figure 3.14, 3.15 and 3.16 shows the same scenario with velocities 75, 100 and 120 Kilometer per hour. From Figure 3.13 to 3.16 it is seen that performance all algorithms deteriorate as the speed increases. However, at lower speeds AdaBoost gets a marginal gain over MMSE and at higher speeds both AdaBoost and MMSE perform equally. Again, both AdaBoost and MMSE outperform LS in mobility scenario also.

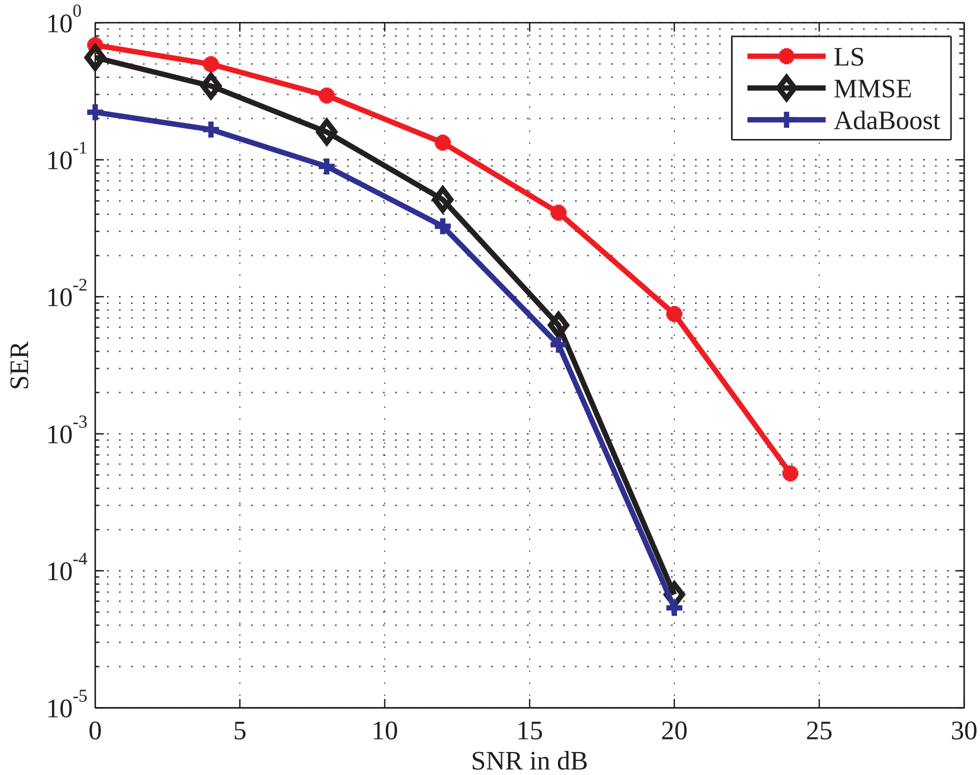


Figure 3.9: Performance comparison under non line of sight channel [.26 .93 .26]

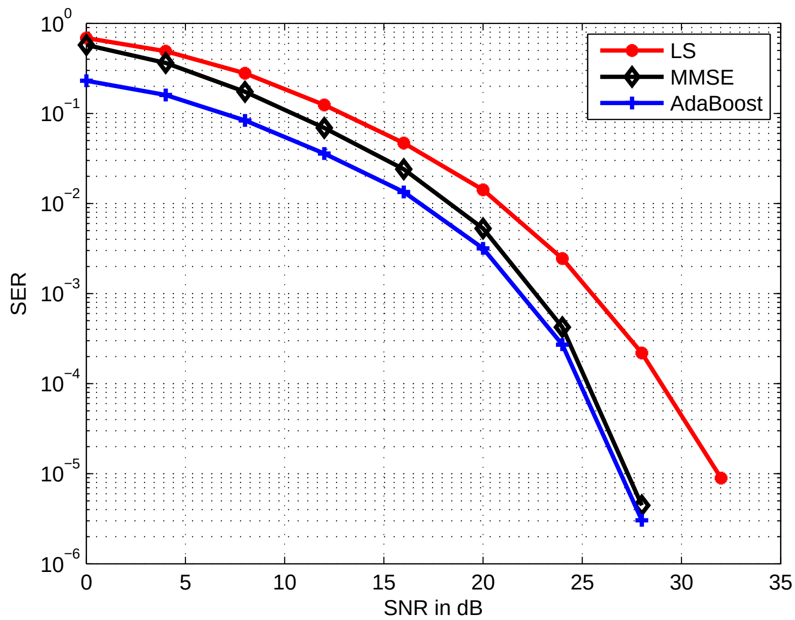


Figure 3.10: Performance comparison of different receivers for 3 tap Rayleigh channel

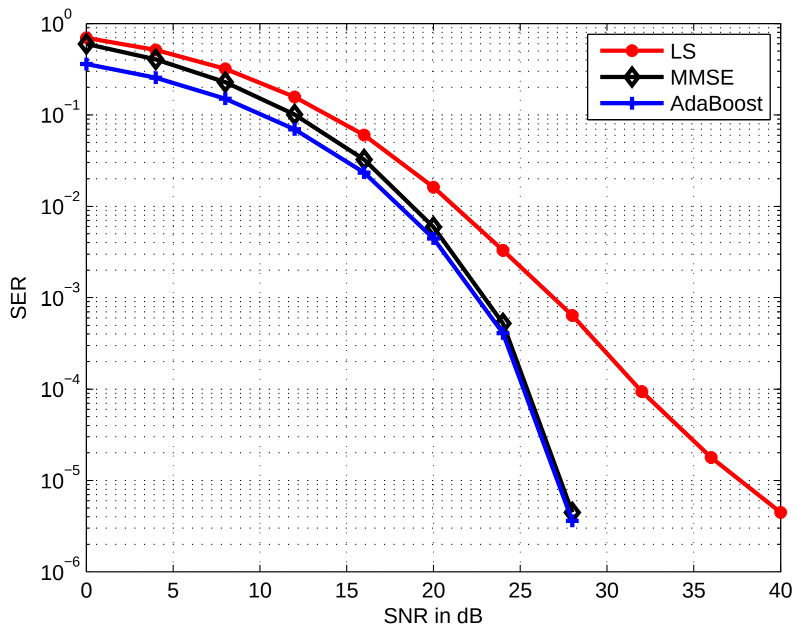


Figure 3.11: Performance comparison of different receivers for 5 tap Rayleigh channel

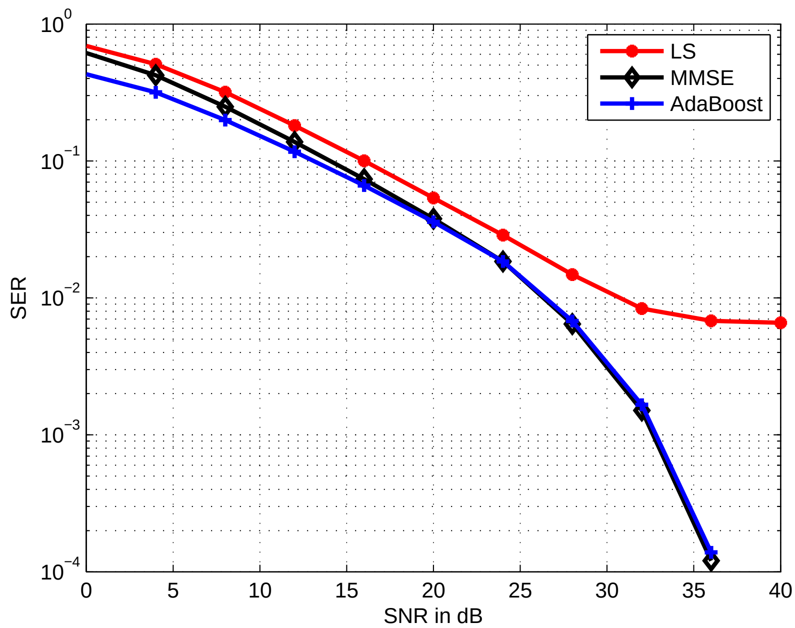


Figure 3.12: Performance comparison of different receivers for 7 tap Rayleigh channel

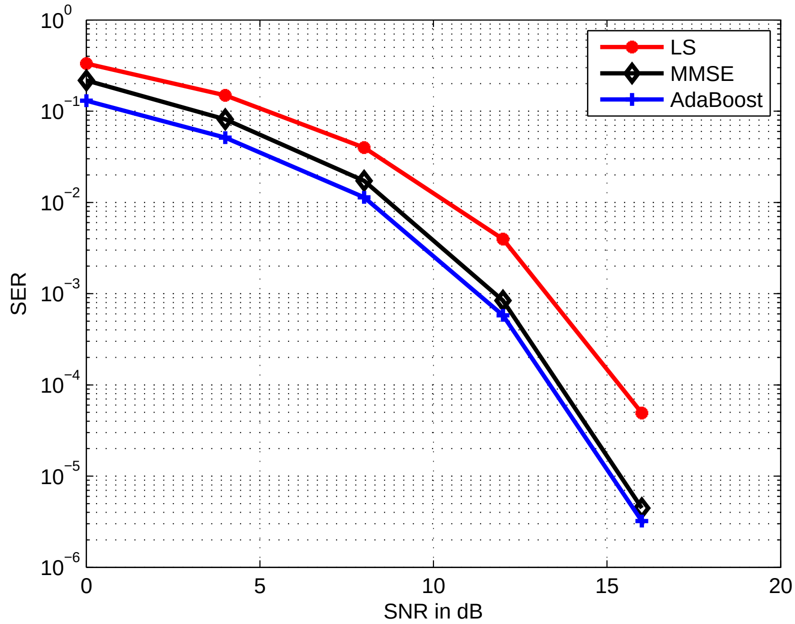


Figure 3.13: Performance comparison of receivers for Rayleigh channel with an user at 50 Km/h

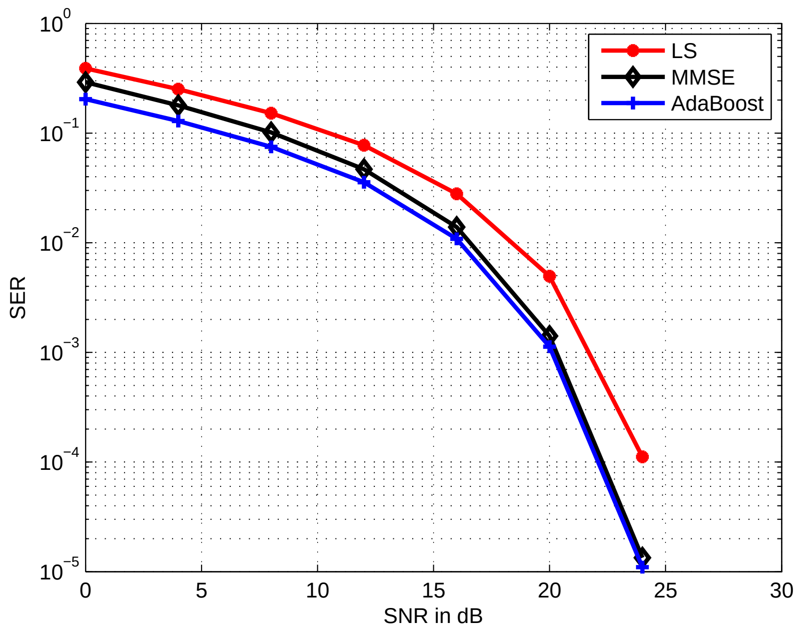


Figure 3.14: Performance comparison of receivers for Rayleigh channel with an user at 75 Km/h

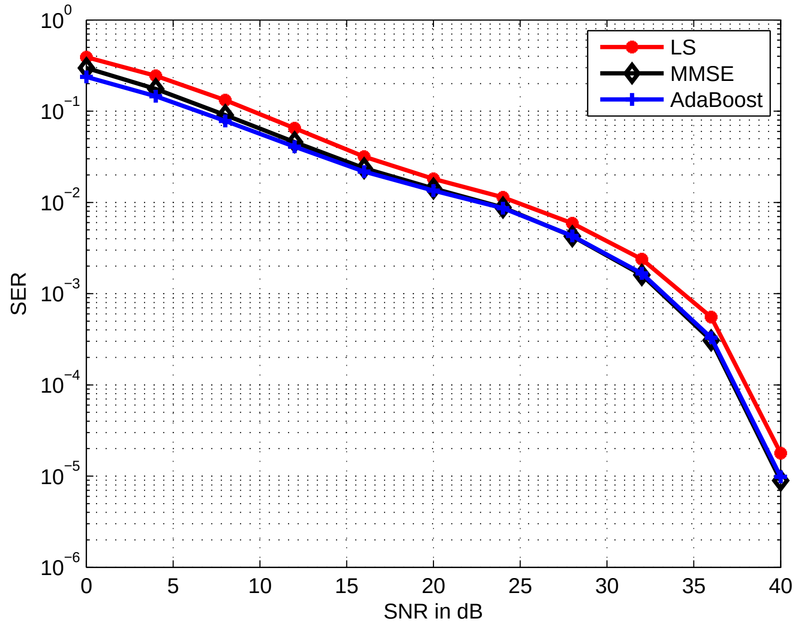


Figure 3.15: Performance comparison of receivers for Rayleigh channel with an user at 100 Km/h

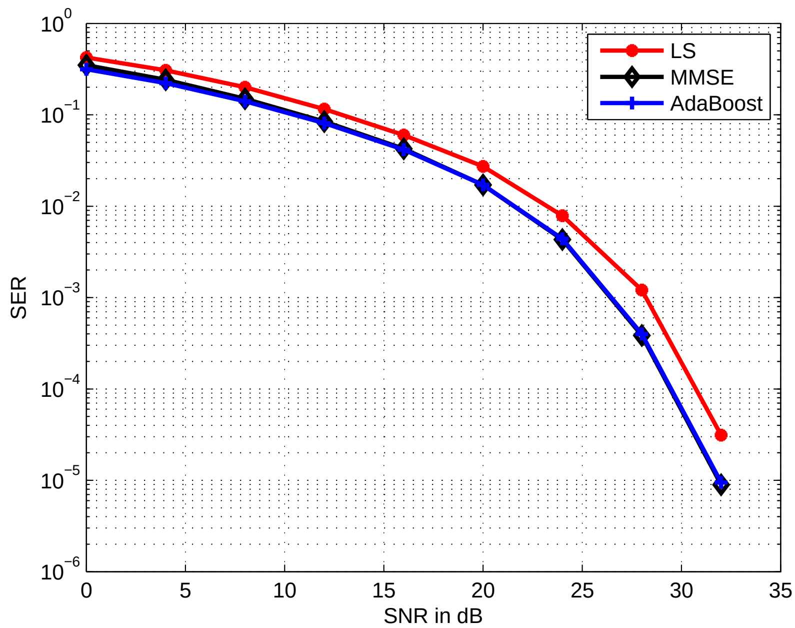


Figure 3.16: Performance comparison of receivers for Rayleigh channel with an user at120 Km/h

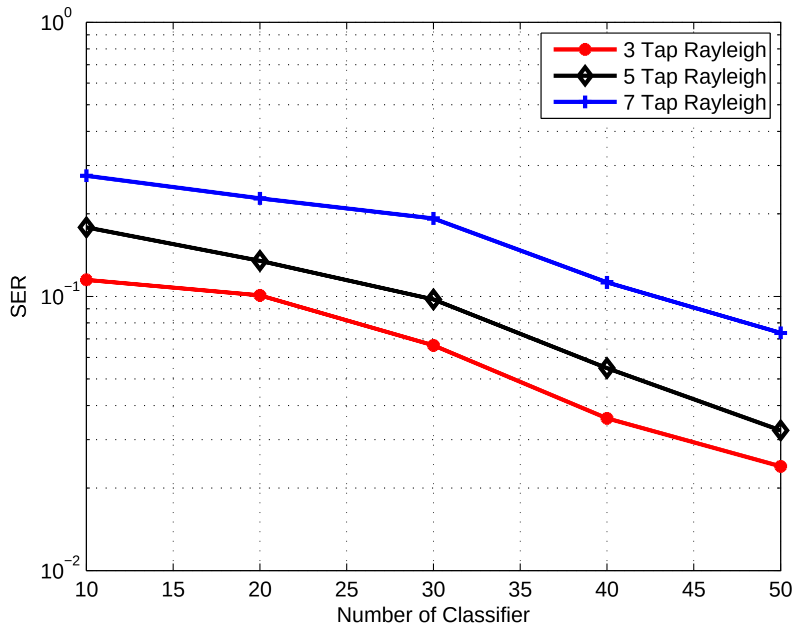


Figure 3.17: Performance of AdaBoost receiver with varying number of classifier for different channels at 20 dB SNR

Figure 3.17 shows the performance of proposed AdaBoost based symbol recovery algorithm with varying the number of classifiers at SNR of 20 dB. This simulation was carried out for three channels with 3, 5 and 7 taps. It is seen that as we go increasing the number of classifiers the BER performance improves, however, with increase in the channel taps the performance degrades.

3.6.1 Computational complexity analysis

The computational complexity of the MMSE increases exponentially as the number of carrier increases. Among all algorithms discussed here, LS has least computational complexity, as it has a single vector division. So the complexity of LS is $O(N)$, where N is the DFT size. For the MMSE the computational complexity will be larger than the LS as it carries some inverse matrix operations. For the MMSE the computational complexity is $O(5N^3)$ [65]. For the proposed Adaboost based symbol recovery case the computational complexity calculation is little different. In the training stage, the computational complexity of the AdaBoot algorithm arises from the construction of the decision stumps to built a strong classifier. For the construction of the decision stumps, all samples are searched for each feature; thus, the computational complexity for constructing the decision stumps is $O(nN)$, where n is the number of samples. There are T iterations for constructing the strong classifier. Therefore, in the training stage of the AdaBoost algorithm, the computational complexity is only $O(nTM)$

3.7 Summary

In this chapter the application of a pattern classification algorithm, AdaBoost, for efficient symbol recovery at OFDM receiver is presented. Different channel estimation algorithms like LS, MMSE, BLUE were discussed. Working principle of AdaBoost algorithm through example was presented. Channel estimation aided symbol recovery through AdaBoost algorithm was described. A detailed simulation result analysis along with computational complexity analysis was made.

4

Successive Addition Subtraction (SAS) Pre-processed DCT aided PAPR reduction in OFDM

"No problem can be solved from the same level of consciousness that created it".

Albert Einstein

Contents

This chapter starts with a brief introduction on PAPR. Mathematical formulation of PAPR and its minimization with different algorithm is discussed. Following this a successive addition subtraction preprocessed DCT based PAPR reduction method is proposed. The detailed computational complexity for different techniques are analyzed. Later a brief introduction on MIMO sytem is presented. A STBC MIMO OFDM system is considered and the application of the proposed PAPR reduction method to STBC MIMO OFDM is carried out. For MIMO system again the problem has been revisited. Performance of the proposed PAPR method is compared with other techniques and computational complexity for each of th algorithm in MIMO OFDM system is discussed.

Orthogonal frequency division multiplexing has been used as a standard solution for high data rate wireless communication. The need of simple equalization and high spectral efficiency has made this technique a promising candidate for modern wireless communication systems. Orthogonal frequency division multiplexing is a multi-carrier communication method, where it divides a high data rate input data stream into a number of low data rate parallel streams. The multiple low data rate parallel strings are then transmitted through multiple orthogonal sub-carriers. These multiple sub-carriers make the system a multi-carrier communication system. In a multi-carrier communication system data are sent through sub-carriers. At the transmitter, before transmitting, data of each sub-carrier are added up in time domain. Data that are in same phase add up and produces a high peak signal in time domain. Under this process the signal power can potentially exceed the linear range of transmitter power amplifier. In a communication system, operation of the transmitter power amplifier is restricted by its linear range. Any input signal that has an amplitude more than the transmitter power amplifier linear range results in signal distortion. This demands the input signal at the transmitter to have low PAPR. This chapter presents a new method of reducing the peak to average power ratio in OFDM systems. The proposed method is based on discrete cosine transform aided successive addition and subtraction of symbols in side the single orthogonal frequency division multiplexing frame. Performance of the proposed method is evaluated under different conditions.

4.1 Introduction

OFDM is an orthogonal multi-carrier communication system characterized by bandwidth efficiency, high data rate and immunity to fading channels. For the above benefits it has been implemented in many modern communication systems. Although OFDM gives many advantages, it suffers from many technical limitations. Some of these include tight frequency synchronization, time offset, PAPR and channel estimation. Researchers around the world are working on these problems and many other aspects to make OFDM more attractive candidate for future communication applications.

In a multicarrier communication system, like OFDM, independent phases of sub-carriers lead to either constructive or destructive effect. When all sub-carriers have same phase, constructive effect results in high peak amplitude resulting in high PAPR of the signal. If amplitude of the OFDM signal is greater than linear range of transmitter amplifier, the amplifier Q-point moves to operate in saturation region leading to nonlinear amplification. When amplifiers are designed to work with high dynamic range, their efficiency suffers leading to low battery life and carbon foot print. Mitigation of these effects is essential for improved system performance.

Shannon–Hartley theorem says that the number of average bits per second transmitted is proportional to the average power transmitted. Hence, reduction in PAPR can result in a system that can either transmit more bits per second with the same hardware, or transmit the same bits per second with lower-power hardware (and therefore lower electricity costs [66, Page 8]) and therefore less expensive hardware, or both. Additionally PAPR also causes inter-modulation between the sub-carriers and distorts the transmit signal constellation.

The simplest technique to mitigate nonlinearity around the peak is clipping. Since OFDM signal is bounded in frequency and not in time, clipping affects in-band and out-band radiations, thereby affecting the orthogonality among sub-carriers. Clipping techniques include clipping and filtering, peak windowing, and peak canceling [32,33,67,68].

Another method to overcome PAPR issues is coding technique, where specific code words are used before modulation to minimize the PAPR. Though, coding technique has no distortion effect and no out-of-bound radiation, it has adverse effect on bandwidth efficiency as the code rate is reduced. Another disadvantage of this technique is the complexity associated to find best codes. If large number of sub-carriers are used, then a large memory size is required to store the look up table for coding and decoding. Some of the coding techniques used for PAPR include Golay code [35,69–73], Reed Muller code [36,37], Hadamard code [34] and M sequence codes [74,75].

Scrambling technique is another technique used for PAPR reduction. This method is a probabilistic approach, where the input data block of the OFDM symbols are scrambled (i.e multiplied with different phase), thus resulting in OFDM symbols with minimum PAPR to be chosen to be transmitted. The resulting OFDM signal does not suffer from out of bound power but the spectral efficiency decreases. Again, computational complexity of implementation increases with increase in the number of subcarrier. Few of techniques based on this method include partial transmit sequence (PTS) [38–40,76–78], selective mapping (SLM) technique [79–81], tone injection (TI) technique and tone reservation (TR) technique [82].

Discrete Fourier Transform (DFT) spreading has been seen to be useful for minimizing the PAPR. This technique is specifically useful for mobile terminals and they are used in uplink transmission. In this method, the input signal is spread with DFT that can be subsequently taken by IFFT. This technique reduces the PAPR of the OFDM signal to an extent similar to single carrier transmission [83–86].

Present research direction in PAPR reduction are based on modified SLM technique [80,81], PTS technique [39,40,87], and DCT based PAPR reduction technique [81]. Above studies shows that DCT based methods significantly reduces the PAPR. This chapter proposes a new PAPR reduction method that based on iterative addition and subtraction of OFDM symbols followed by DCT operation. This technique is seen to improve the performance of DCT based PAPR reduction.

4.2 System Model

The block diagram of a OFDM system was presented in figure 3.1. Detailed mathematical analysis were also carried out in Chapter 3. From the preceding chapter we know that (Ref to (3.3))

$$y_g(n) = x_g(n) \otimes h(n) \ + \ w(n) \tag{4.1}$$

$x_g(n)$ is the transmitted signal with guard band. $x_g(n)$ is originally generated from $x(n)$ as described in chapter 3. PAPR is associated with the time domain signal. Here the transmitted time domain signal is $x(n)$. In communication system baseband signal is transmitted with a transmitted pulse. So the multi-amplitude-multi-phase sequence of $x(n)$ can be represented as

$$s(t) = \sum_{k=1}^{N} x(n) g(t - kT_s) \tag{4.2}$$

Where $g(t)$ is transmitted pulse and T_s symbol duration. The PAPR is defined as the ratio of maximum power to the average power of complex signal. Mathematically it can be presented as

$$PAPR\{s(t)\} \ = \ \frac{max|s(t)|^2}{E\{|s(t)|^2\}}$$

In OFDM system maximum amplitude appears when all subcarrier components appear in same phase and results in $PAPR = N$. For instance, let us consider an OFDM signal which is the sum of multiple sinusoidals having frequency separation $\frac{1}{T_s}$. Each sinusoidal gets modulated by independent information. The transmitted signal can be represented as,

$$s(t) = \sum_{k=0}^{N-1} a_k e^{\frac{j2\pi ki}{T_s}}$$

where a_k is kth sub-carrier information signal and the signal contains N number sub-carrier. For simplicity, let us assume that a_k=1 for all sub-carriers. In this scenario, the peak value of the signal can be presented as,

$$\begin{aligned}
\max\left[s(t)s^*(t)\right] &= \max\left[\sum_{k=0}^{N-1} a_k e^{\frac{j2\pi ki}{T_s}} \sum_{k=0}^{N-1} a_k^* e^{\frac{-j2\pi ki}{T_s}}\right] && (4.3)\\
&= \max\left[a_k a_k^* \sum_{k=0}^{N-1}\sum_{k=0}^{N-1} e^{\frac{j2\pi ki}{T_s}} e^{\frac{-j2\pi ki}{T_s}}\right] && (4.4)\\
&= N^2 && (4.5)
\end{aligned}$$

The mean square value of the signal is,

$$\begin{aligned}
E\left[s(t)s^*(t)\right] &= E\left[\sum_{k=0}^{N-1} a_k e^{\frac{j2\pi ki}{T_s}} \sum_{k=0}^{N-1} a_k^* e^{\frac{-j2\pi ki}{T_s}}\right] && (4.6)\\
&= E\left[a_k a_k^* \sum_{k=0}^{N-1}\sum_{k=0}^{N-1} e^{\frac{j2\pi ki}{T_s}} e^{\frac{-j2\pi ki}{T_s}}\right] && (4.7)\\
&= N && (4.8)
\end{aligned}$$

the peak to average power ratio for the above OFDM system with N sub-carriers is,

$$PAPR = \frac{N^2}{N} = N$$

It is reasonably intuitive, that the above value corresponds to the maximum value of PAPR (when all the sub-carriers are equally modulated, all the sub-carriers align in phase and the peak value hits the maximum).

The PAPR is usually calculated through cumulative distribution function (CDF) which is a probabilistic approach. Complex OFDM symbols are composed of real parts and imaginary parts. These real and imaginary parts are asymptotically Gaussian distribution for a large number of sub-carriers. Hence, the amplitude of OFDM symbols follow Rayleigh distribution. Assuming that the average power of $s(t)$ is equal to one, $E\{|s(t)|^2\} = 1$; then z_n are i.i.d. Rayleigh random variables normalized with its own average power will have Probability Density Function (PDF) [27]

$$f_{Z_n}(Z) = \frac{z}{\sigma^2} e^{-\frac{z^2}{2\sigma^2}} = 2ze^{-z^2}$$

where Z_n is the magnitude of complex samples $\{s(nT_s/N)\}_{n=0}^{N-1}$ and $E\{Z_n^2\} = 2\sigma^2 = 1$.

CDF Z_{max} can be presented as

$$\begin{aligned} F_{Z_{max}}(z) &= P(Z_{max}) < z \\ &= P(Z_0 < z).P(Z_1 < z) \dots P(Z_{N-1} < z) \\ &= (1 - e^{-z^2})^N \end{aligned} \tag{4.9}$$

where

$$Z_{max} = \max_{n=0,1,2\dots,N-1} \{Z_n\}$$

is called the crest factor (CF).

To find the probability that the CF exceeds z complementary CDF (CCDF). CCDF can be used.

$$\begin{aligned} \tilde{F}_{Z_{max}}(z) &= P(Z_{max}) > z \\ &= 1 - P(Z_{max} \leq z) \\ &= 1 - F_{max}(z) \\ &= 1 - (1 - e^{-z^2})^N \end{aligned} \tag{4.10}$$

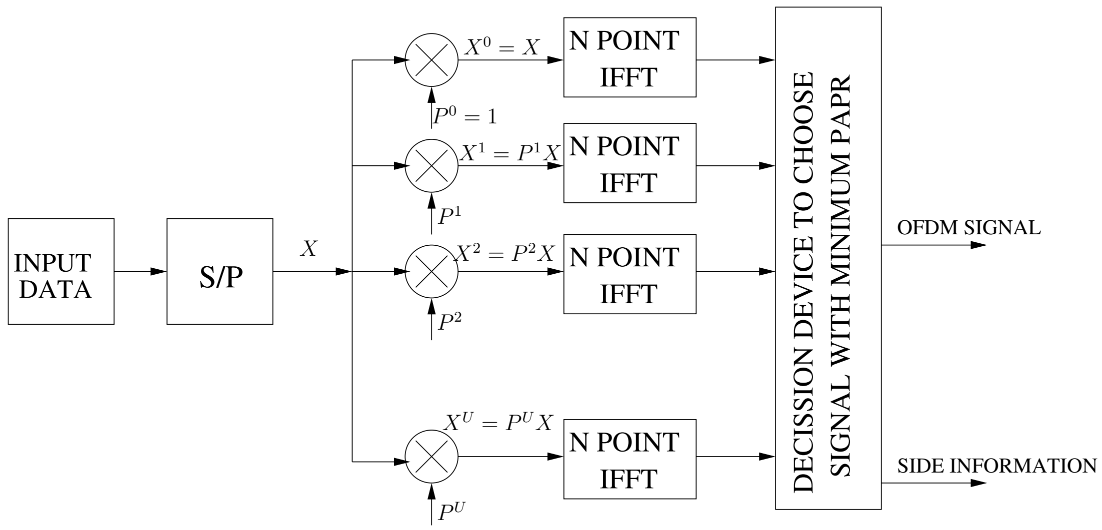


Figure 4.1: Selective Mapping Technique for PAPR reduction

where $\tilde{F}_{Z_{max}}(z)$ is the Complementary Cumulative Distribution function (CCDF).

4.3 PAPR reduction techniques: A review

Different type of PAPR reduction techniques were listed in section 4.1. This section, describes the SLM, PTS techniques. Following this a new PAPR reduction technique is proposed. SLM and PTS schemes have been very popular in minimizing PAPR effectively. So, performance of proposed method is compared against SLM and PTS technique.

4.3.1 Selective mapping (SLM) for PAPR

In SLM technique the input data sequence is multiplied by U number of phases independently. The block diagram for selective mapping technique is shown in Figure. 4.1. The input data block

$$X = [X(0)\ X(1)\ \ldots\ X(N-1)] \tag{4.11}$$

is multiplied with different independent phases

$$P^U = [P_0^U \; P_1^U \; \dots \; P_{N-1}^U] \tag{4.12}$$

P^U is the Uth block phase vector. Where $P_v^u = e^{j\phi_v^u}$ and $\phi_v^u \in [1, 2\pi)$ for $v = 0, 1, \dots \; N-1$ and $u = 1, 2, \dots \; U$. The modified data is then represented by

$$X^U = [X^U(0) \; X^U(1) \; X^U(2) \; \dots \; X^U(N-1)]^T \tag{4.13}$$

IFFT of U number of independent sequences, X^U, are computed. After IFFT operation the time domain signal is represented as

$$x^U = [x^U(0) \; x^U(1) \; x^U(2) \; \dots \; x^U(N-1)]^T \tag{4.14}$$

The decision device calculates, PAPR of each of independent x^u and chooses the signal with minimum PAPR to be transmitted. The corresponding phase sequence for which PAPR is minimum is sent as side information. The phase for the subcarrier with minimum PAPR is given by

$$\tilde{U} = \underset{u=1,2,\dots U}{\arg\min} \left(\max_{n=1,2,\dots,N-1} |x^u(n)| \right) \tag{4.15}$$

$\tilde{U}$ is the phase vector with minimum PAPR. The concept here is any one single data vector of the transmitter signal can have multiple representations. Out of these, lowest PAPR time domain vector is selected for transmission [31,79,80,88]. This technique provides lowest PAPR but the complexity increases as SLM scheme needs multiple IFFT operation.

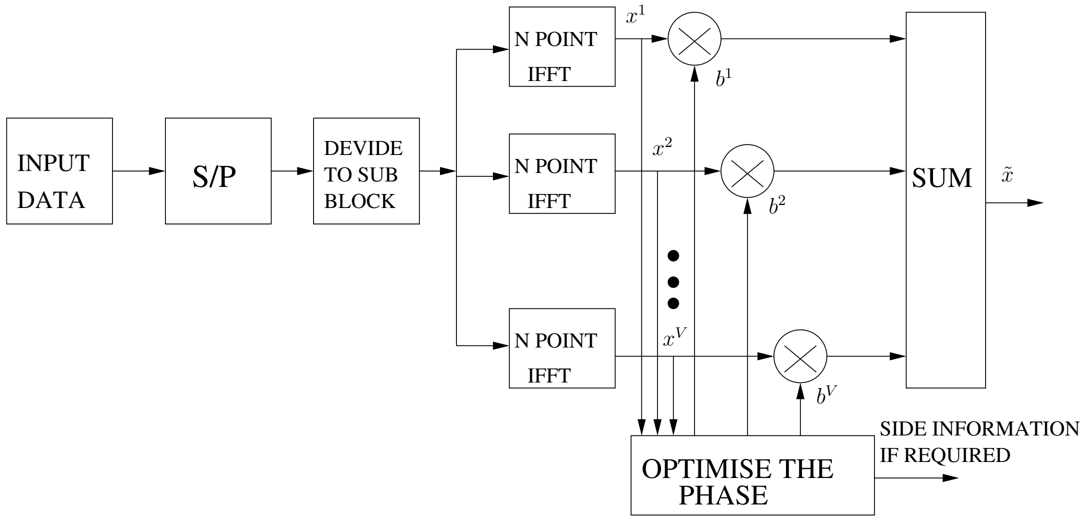


Figure 4.2: Partial Transmit Sequence Scheme for PAPR reduction

4.3.2 Partial Transmit Sequence (PTS) technique

Another popular technique for PAPR reduction is PTS. The block diagram of this scheme is presented in Figure. 4.2. This method is similar to SLM, but divides the frequency vector into smaller blocks before applying the phase transformations [38–40,76–78]. In PTS scheme the input data block of length N is divided into V disjoint sub blocks, which can be written as

$$X = [X^1\, X^2\, \ldots\, X^V]$$

where X^i, for $i = 1, 2, \ldots, V$, are sub blocks that are located consecutively and are of equal length. In case of SLM technique, scrambling is applied to each sub-carrier whereas in case of PTS scheme scrambling is applied to a set of sub-carrier which constitutes sub block. Each of the sub block is multiplied by a phase factor $b^v = e^{j\phi_v}$ for $v = 1, 2, \ldots V$. Subsequently, the IFFT of each sub block is computed. Hence, the time domain signal after IFFT operation is given by

$$x = IFFT\left\{\sum_{v=1}^{V} b^v\ X^v\right\}$$
$$= \sum_{v=1}^{V} b^v\ IFFT(X^v)$$
$$= \sum_{v=1}^{V} b^v\ x^v$$

x^v is called the partial transmit sequence. The phase vector for minimum PAPR is thus given by

$$\tilde{b}^1\ \tilde{b}^2\ \ldots \tilde{b}^V = \underset{[b^1\ b^2\ \ldots b^V]}{\arg\min}\left(\max_{n=0,1,\ \ldots N-1}\left|\sum_{v=1}^{V} b^v\ x^v(n)\right|\right) \tag{4.16}$$

The above equation calculates the set of phases for which the PAPR will be minimum. The corresponding time domain signal with minimum PAPR is given by

$$\tilde{x} = \sum_{v=1}^{V} b^v\ x^v$$

PTS has the lowest PAPR and is optimal when uses all possible constellations as phase factor. It has little redundancy. However, the system complexity increases with increase in number of sub-carriers, number of sub-blocks and phase factor.

4.4 SAS preprocessed DCT based PAPR reduction

Basic principle behind this method is to change the phase of each successive symbols inside the OFDM frame. For N number of sub-carriers there are N symbols denoted as $n = 0, 1, 2, \ldots, N-1$ OFDM symbols. First OFDM symbol to be transmitted as it is. From second symbol to onward, Each odd OFDM symbol is multiplied by $+1$ and each even OFDM symbol is multiplied by -1. The second OFDM symbol to be transmitted is addition of first two OFDM symbols (after multiplication by either $+1$ or -1). Similarly, the process goes on for N number symbols. After getting the transformed N OFDM symbols, the DCT of the transformed signal is taken. Then it is passed through IFFT block. Mathematically the transformed $X(K)$ is given by

$$X_t(k) = \begin{cases} X(k) & \textit{for } k\textit{=0} \\ \sum_{i=even}^{K=k} X(i) - \sum_{i=odd}^{K=k} X(i) & k\textit{=1,2,}\ldots\textit{,N-1} \end{cases}$$

where $X_t(k)$ is the transformed signal.

In matrix representation, the preprocessed block X_t can be given as

$$\begin{aligned} X_t &= \begin{bmatrix} 1 & 0 & 0 & 0 & \cdots & 0 \\ 1 & -1 & 0 & 0 & \cdots & 0 \\ 1 & -1 & 1 & 0 & \cdots & 0 \\ 1 & -1 & 1 & -1 & \cdots & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 1 & -1 & 1 & -1 & \cdots & -1 \end{bmatrix}_{N\times N} \begin{bmatrix} X(0) \\ X(1) \\ X(2) \\ \vdots \\ X(N-1) \end{bmatrix}_{N\times 1} \\ &= \begin{bmatrix} X(0) \\ X(0) - X(1) \\ X(0) - X(1) + X(2) \\ \vdots \\ X(0) - X(1) + X(2) - \cdots X(N-1) \end{bmatrix}_{N\times 1} \end{aligned} \tag{4.17}$$

It is a well known fact that the DCT decorrelates a data sequence. Hence, application of DCT before IFFT for PAPR reduction significantly reduces the auto-correlation in data sequence [89]. The one-dimensional DCT of length N is given as

$$X_k = \alpha(k) \sum_{n=0}^{N-1} x_n \cos\left[\frac{\pi}{N}\left(n + \frac{1}{2}\right)k\right] \qquad k = 0, \ldots, N-1. \tag{4.18}$$

and the inverse transformation is given as

$$x_n = \sum_{k=0}^{N-1} \alpha(k) X_k \cos\left[\frac{\pi}{N}\left(n+\frac{1}{2}\right)k\right] \qquad n = 0,\ldots,N-1. \tag{4.19}$$

Where $\alpha(k)$ is a constant and is represented by

$$\alpha(k) = \begin{cases} \frac{1}{\sqrt{N}}, & \text{for } k = 0 \\ \frac{2}{\sqrt{N}}, & \text{for } k \neq 0 \end{cases} \tag{4.20}$$

(4.18) can be presented in matrix form by

$$X_t = C_N \; X \tag{4.21}$$

where, C_N is the DCT matrix of dimension $N \times N$ and both X and x are of dimension $N \times 1$. The rows and columns of the DCT matrix, C_N, are orthogonal matrix vectors. This property of the DCT can be used to reduce the peak power of OFDM signals. Tellambura *et al.* [90] claimed that, there is a relation between the PAPR of an OFDM signal and the aperiodic autocorrelation function (ACF) of an input vector. Assume $\rho(i)$ is the ACF of a signal vector, X, then:

$$\rho(i) = \sum_{k=0}^{N-1-i} X_{k+i} X_k^* \quad \text{for} \quad i = 0, 1, \ldots, N-1 \tag{4.22}$$

Superscript '*' represent the complex conjugate. From [90], the PAPR of the transformed OFDM signal is bounded by

$$PAPR \leq 1 + \frac{2}{N} \sum_{i=0}^{N-1} |\rho(i)| \tag{4.23}$$

Let

$$\lambda = \sum_{i=0}^{N-1} |\rho(i)|$$

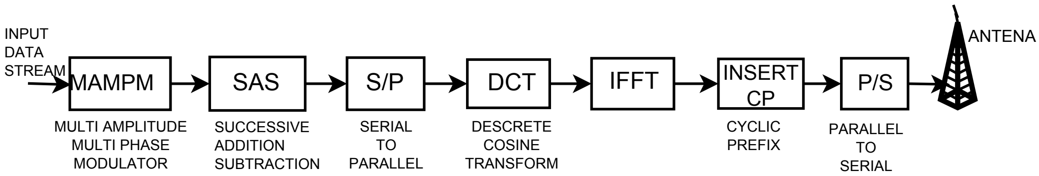


Figure 4.3: Transmitter using the proposed method of PAPR reduction

Then any input vector with lower λ yeilds a signal with lower PAPR in OFDM system. It has been proved that if input vector passed by DCT transform before IFFT, the $\rho(i)$ and thus PAPR could be reduced [90].

During the process of successive addition and subtraction, the transformed data may lose its orthogonality before IFFT process. Hence, a DCT operation also helps to restore the orthogonality before IFFT operation and it further reduces PAPR of the data. Hence, the time domain signal after IFFT is presented as

$$x(n) = IFFT\{DCT\{X_t\}\}$$

The block diagram of the transmitter using the proposed method of PAPR reduction is shown in Fig. 4.3

In the receiver, data can be retrieved by simple differentiation. The difference procedure is shown in Figure 4.4. The difference process starts from bottom of the column

$$\mathrm{y} = \begin{array}{cc} X(0) & \text{N-1 step difference} \\ X(0)-X(1) & \\ X(0)-X(1)+X(2) & \text{N-2 step difference} \\ X(0)-X(1)+X(2)-X(3) & \\ \vdots & \\ X(0)-X(1)+X(2)-X(3)...-X(N-1) & \text{1st step difference} \end{array} = \begin{array}{c} X(0) \\ -X(1) \\ \vdots \\ -X(N-1)) \end{array}$$

Figure 4.4: Bottom to up difference method

vector. The first difference is between $N-2$th and $N-1$th elements of the column vector. $N-2$th element is subtracted from $N-1$th element. Similarly, the 2nd

$$\begin{array}{ccccc} 1 & 0 & \cdots & 0 \\ 0 & -1 & 0 & 0 \\ \vdots & 0 & 1 & \vdots \\ \vdots & 0 & \ddots & \vdots \\ 0 & 0 & \cdots & -1 \end{array} \times \begin{array}{c} X(0) \\ -X(1) \\ \\ \\ -X(N-1)) \end{array}$$

Figure 4.5: Multiplication by diagonal matrix to recover the signal

difference is between $N-3$th element and $N-2$th element. Like wise it will go from bottom to up. In this process the transmitted signals are retrieved with alternate positive and negative signs. So, in the next step it should be multiplied by a square diagonal matrix of size $N \times N$, whose diagonal elements contain alternative +1 and -1. The multiplication is shown if Figure 4.5. The transmitted data are now recovered back at the end of the multiplication procedure.

4.5 Simulation study and result

CCDF computes the power complementary to cumulative distribution function from a time domain signal. The CCDF curve shows the amount of time a signal spends above the average power level of the measured signal, or equivalently, the probability that the signal power will be above the average power level. Figure 4.6 shows the performance the PTS algorithm. It is seen that the performance of PTS algorithm increases as the number of sub-block increases. Figure 4.7presents the performance of the SLM technique. It is seen that performance of SLM technique increases by gradually increasing the number of fingers. CCDF of the proposed method was evaluated through simulation. In this simulation QPSK and QAM-16 modulation were used. 512 number of sub-carriers were incorporated for data transmission. Figure 4.8 and Figure 4.9 present the PAPR performance comparison of the proposed SAS preprocessed DCT aided PAPR reduction method using QPSK and QAM16 modulation. From Figure 4.8 it is evident that the proposed method gains a PAPR margin of 3dB lower than the

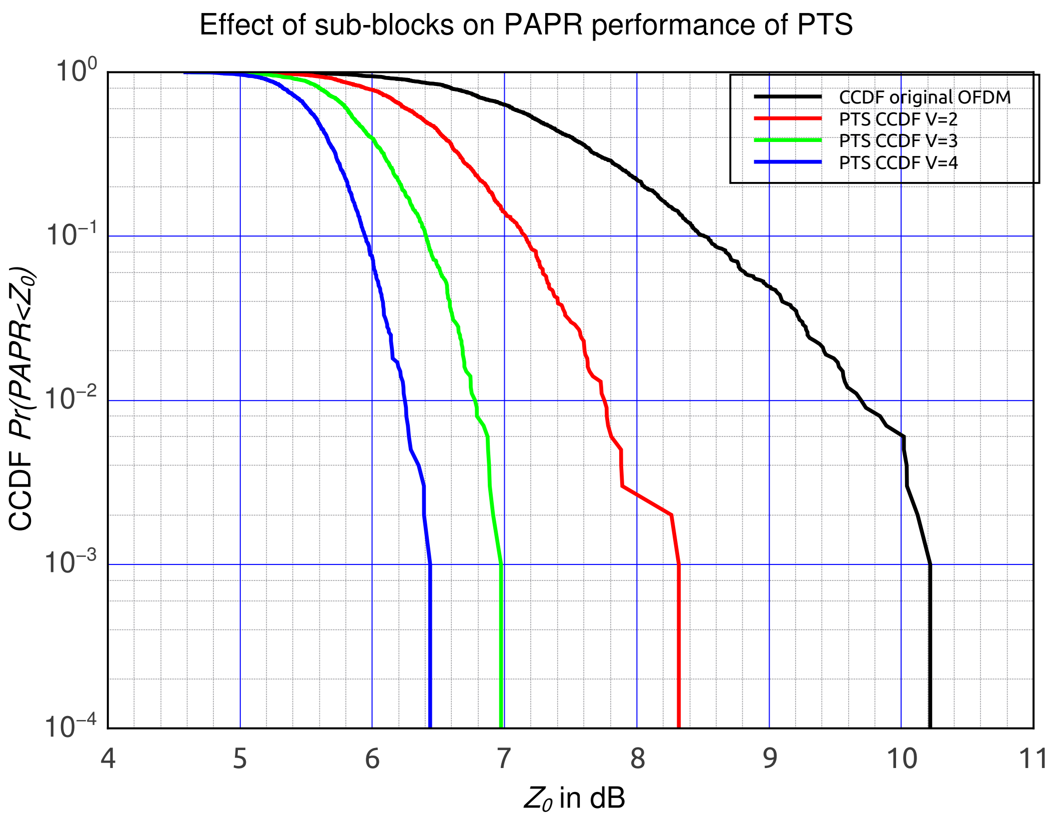


Figure 4.6: PAPR performance of PTS technique using QPSK modulation

theoretical PAPR. Moreover, the performance of proposed method is asymptotically same as of DCT method after a certain threshold of PAPR. At the lower PAPR, the proposed method outperforms the DCT method too. In Figure 4.9 it is seen that performance of proposed method is better when higher level modulation is used. The effect of increasing number of sub-carrier has an adverse effect on the PAPR performance. In the Figure 4.10 a PAPR performance curves with varying number of sub-carriers are portrayed. From this figure it is seen that performance of the proposed technique degrade with increase in number of sub-carriers.

Figure 4.11 shows PAPR performance of different methods like PTS, SLM, DCT and proposed SAS preprocessed DCT aided PAPR reduction method. In this chapter, PTS scheme is performed by dividing the input data block into 4 sub blocks and only two phases (+1 and -1) are used to get minimum PAPR. From Figure 4.11 it is seen that the proposed method performs better than the SLM and DCT Technique. However, at

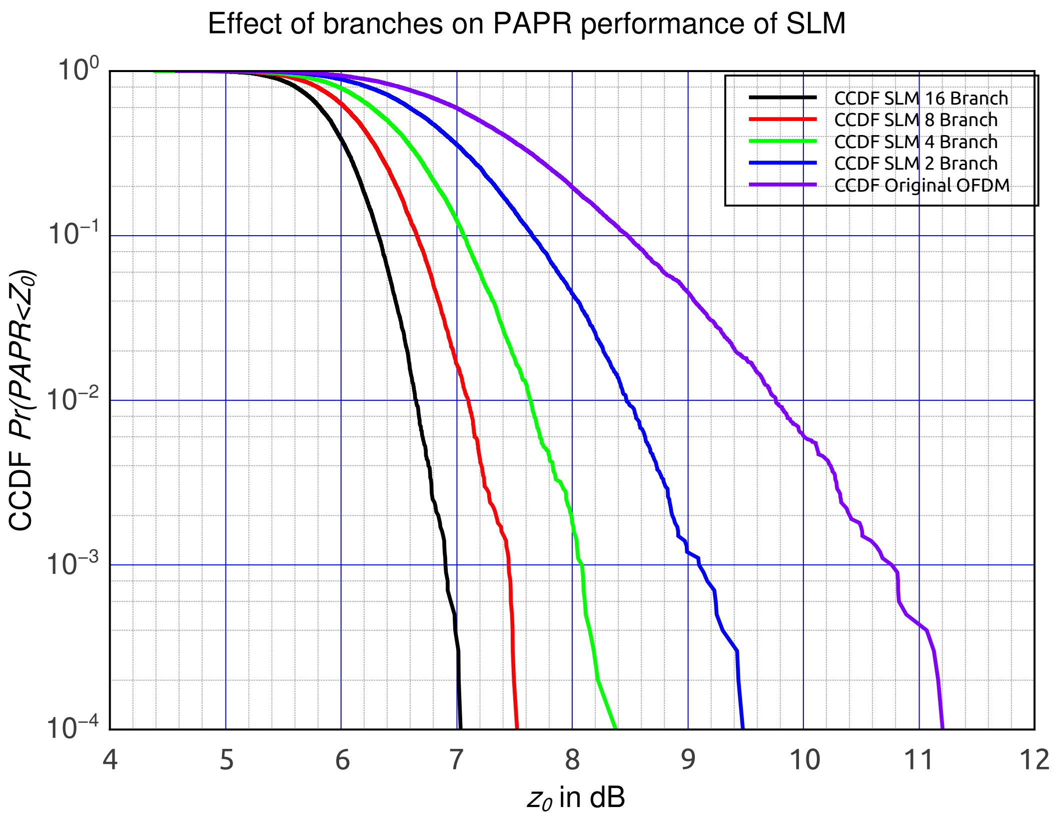


Figure 4.7: PAPR performance of SLM method using QPSK modulation

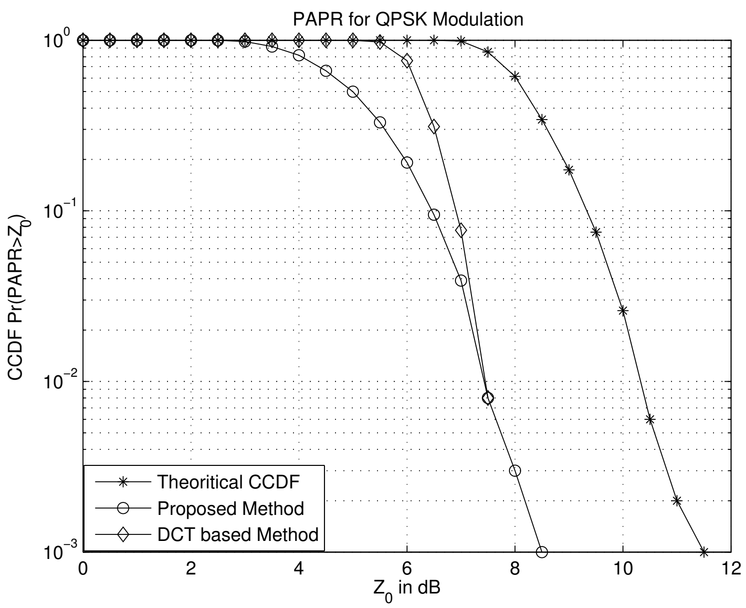


Figure 4.8: PAPR performance of proposed method using QPSK modulation

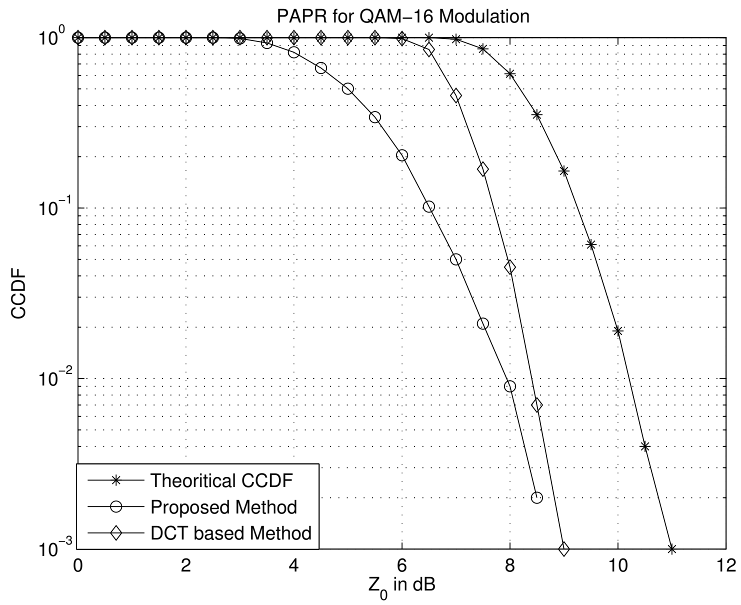


Figure 4.9: PAPR performance comparison of proposed method using QAM-16 modulation

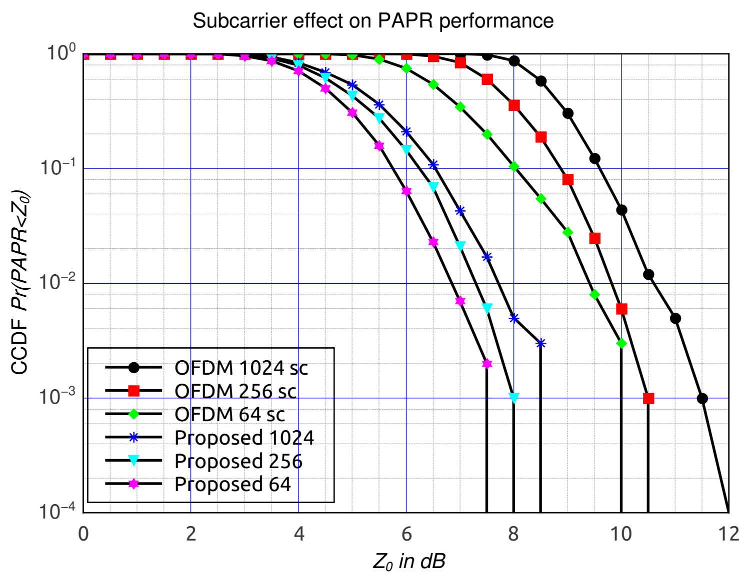


Figure 4.10: PAPR performance comparison proposed SAS-DCT technique with varying number of subcarrier using QPSK modulation

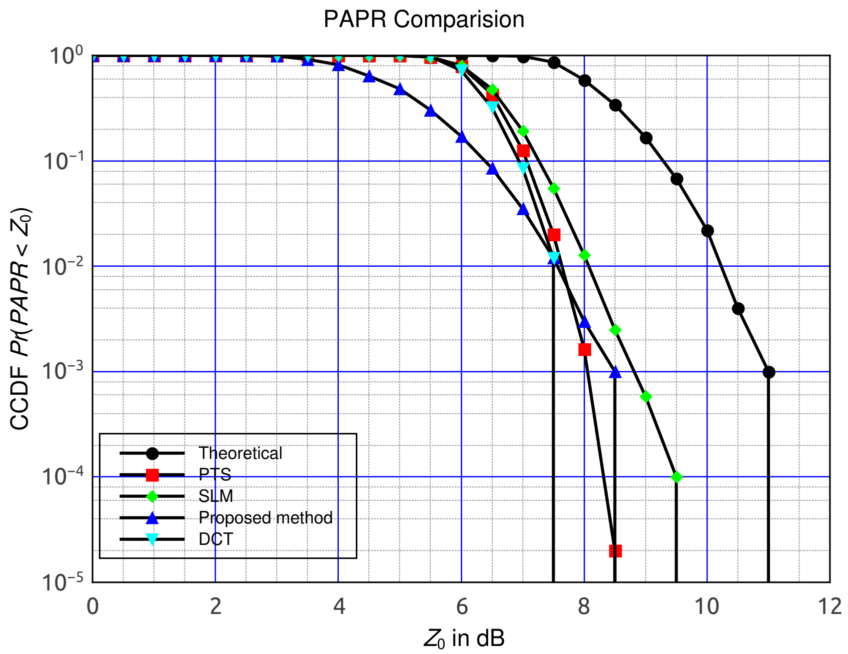


Figure 4.11: PAPR comparison with different techniques

higher PAPR, PTS technique outperforms the proposed method. Phase distribution of the OFDM signal is portrayed in Figure 4.12 and Figure 4.13. From the Figure 4.12 and Figure 4.13 it is seen that, distribution of phases in original OFDM signal has nonuniform distribution as the cumulative count of phases is a nonlinear curve whereas, the proposed SAS method efficiently mitigates the PAPR effect by making uniform distribution of phases. Bit Error Rate (BER) Performance of the link with different algorithms is presented in the Figure 4.14. BER performance was evaluated by taking 512 sub-carriers, 5 tap Rayleigh channel, and QPSK modulation. The BER performance curve clearly indicates that the proposed method outperform to other algorithms such as SLM and PTS.

4.5.1 Computational complexity analysis

From the above findings, it is observed that the performance of PTS technique improves by increasing the number of sub-blocks and the performance of SLM technique improves by increasing number of phase vectors. The proposed algorithm is not based on any partitioning method. Computational complexity of all the PAPR reduction methods,

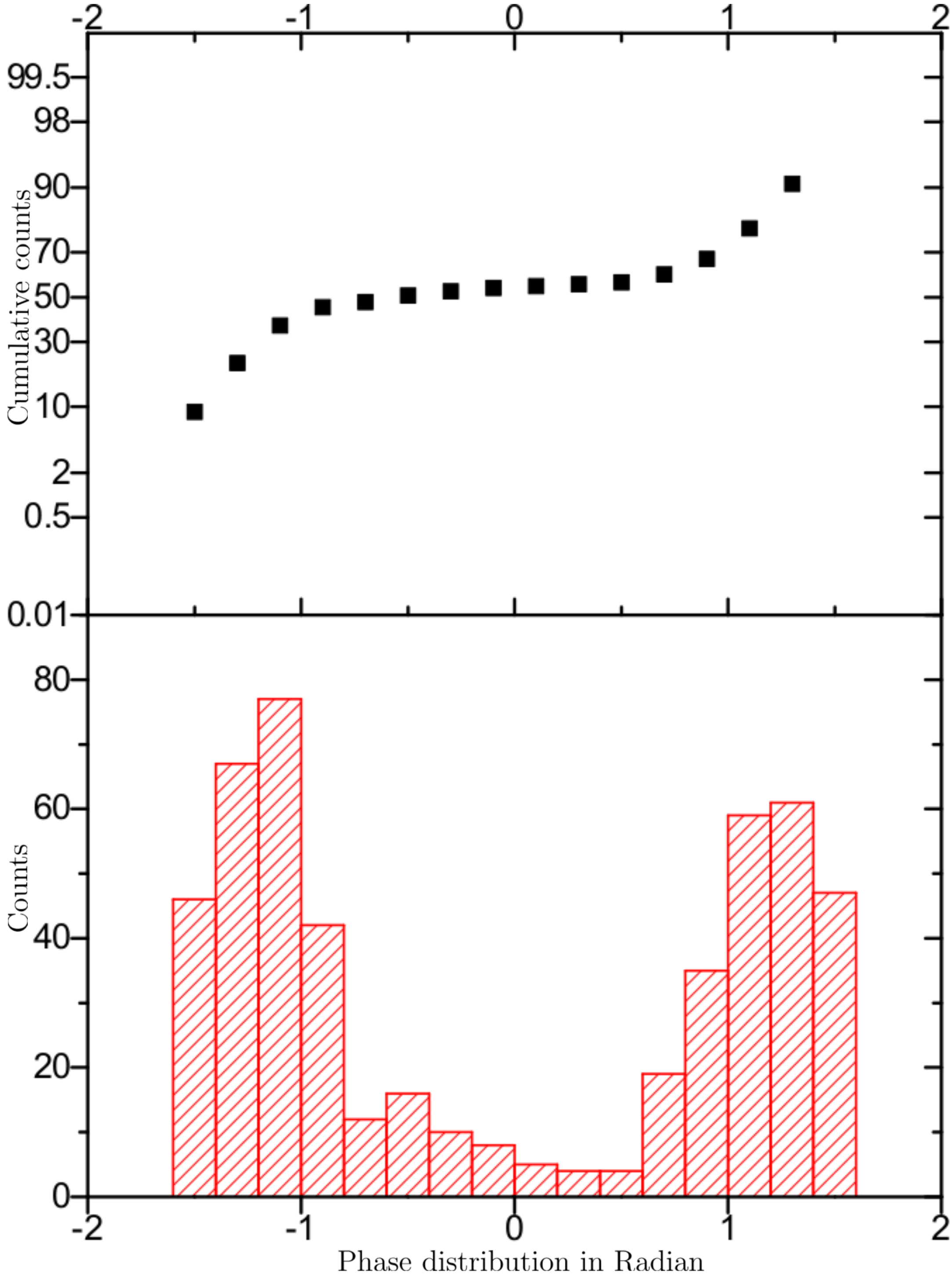


Figure 4.12: Histogram and Phase distribution of original OFDM signal

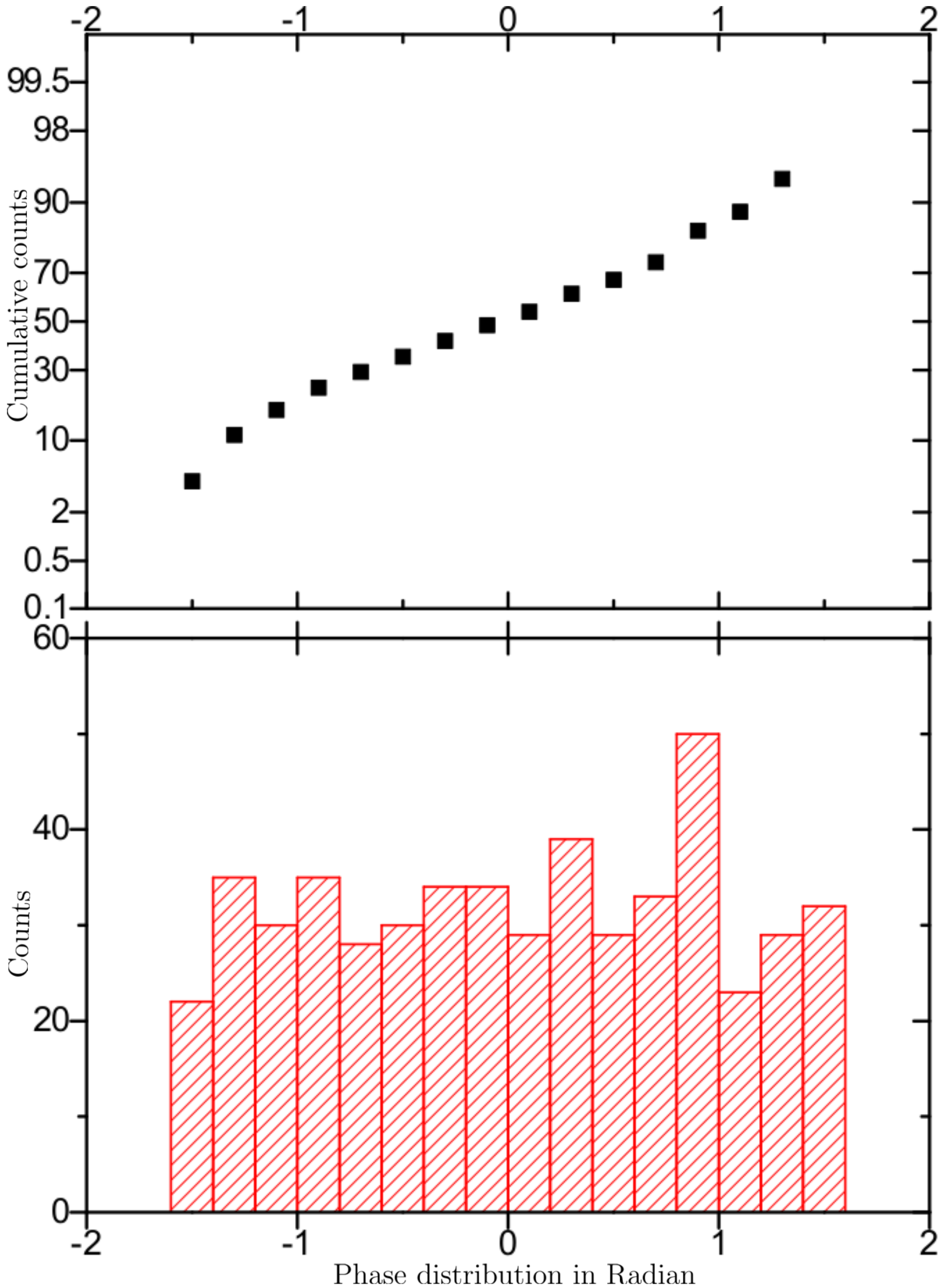


Figure 4.13: Histogram and Phase distribution of SAS-DCT technique

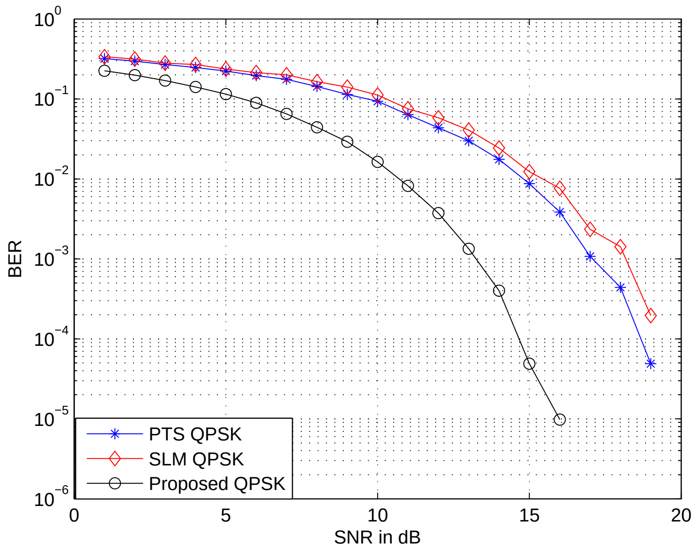


Figure 4.14: BER performance of different techniques

however, is dependant on the number of sub-careers used. Each of the method also undergoes the process of IFFT. Hence, at this point the computational complexity can be divided into two parts. First part deals with the preprocessing computational complexity and the second deals with the number of computation required in IFFT stage.

4.5.1.1 Preprocessing complexity:

Without loss of ambiguity, it is assumed $N = 64, 128, 256, \ldots$ is the number of sub-carriers and $M = 2, 4, 8, 16, \ldots$ is the signalling constellation. Computational complexity for each method is presented in Table 4.2.

Complexity of PTS scheme

In this scheme the data stream is divided into V number of sub-blocks. Each sub-block is multiplied with a phase. W is the number signalling points chosen from M number of constellation points. Each sub-block is multiplied with a phase factor to optimise the PAPR. Hence, there is NW^{V-1} complex multiplications.

SLM method

The OFDM signal is multiplied by U number of phase vectors. Each phase vector contains N number of phases. So there is UN number of complex multiplications are performed.

SAS Method

This method deals with addition and subtraction of symbols. From eqation 4.17, it is clear that there is N number of additions. Furthermore, DCT requires $Nlog_2N$ multiplications and N number of additions.

4.5.1.2 Complexity in IFFT process:

For N point IFFT, it requires $\frac{N}{2}log_2N$ number of complex multiplications and $Nlog_2N$ number of additions. Here, computational complexity of different algorithms at IFFT stage calculated.

PTS method

V number of sub-block data are to be processed in IFFT. Hence, $V\frac{N}{2}log_2N$ of multiplications and $VNlog_2N$ number of additions are required.

SLM method

U number of OFDM symbols each carrying N data points are to be processed in IFFT. Hence, $U\frac{N}{2}log_2N$ of multiplications and $UNlog_2N$ number of additions are required.

SAS Method

Only a single OFDM symbol is to be processed. So, $\frac{N}{2}log_2N$ of multiplications and $Nlog_2N$ number of additions are required.

Hence, computational complexity of different algorithms can be seen in Table 4.7. From Table 4.2 it is seen that complexity of the proposed SAS DCT technique is less comparatively.

Table 4.1: Computational complexity of different PAPR reduction algorithms

Method	Multiplications	Additions
PTS	$NW^{V-1} + V\frac{N}{2}log_2N$	$VNlog_2N$
SLM	$UN + U\frac{N}{2}log_2N$	$UNlog_2N$
SAS	$\frac{N}{2}log_2N + Nlog_2N$	$N + Nlog_2N$

Table 4.2: Computational complexity of different algorithms at preprocessing stage

Method			Number of subcarrier					
			64	128	256	512	1024	2048
PTS	W=2	V=2	128	256	512	1024	2048	4096
		V=3	256	512	1024	2048	4096	8192
		V=4	512	1024	2048	4096	8192	16384
	W=4	V=2	256	512	1024	2048	4096	8192
		V=3	1024	2048	4096	8192	16384	32768
		V=4	4096	8192	16384	32768	65536	131072
	W=8	V=2	512	1024	2048	4096	8192	16384
		V=3	4096	8192	16384	32768	65536	131072
		V=4	32768	65536	131072	262144	524288	1048576
SLM	U=2		128	256	512	1024	2048	4096
	U=4		256	512	1024	2048	4096	8192
	U=8		512	1024	2048	4096	8192	16384
	U=16		1024	2048	4096	8192	16384	32768
SAS			384	896	2048	4608	10240	22528

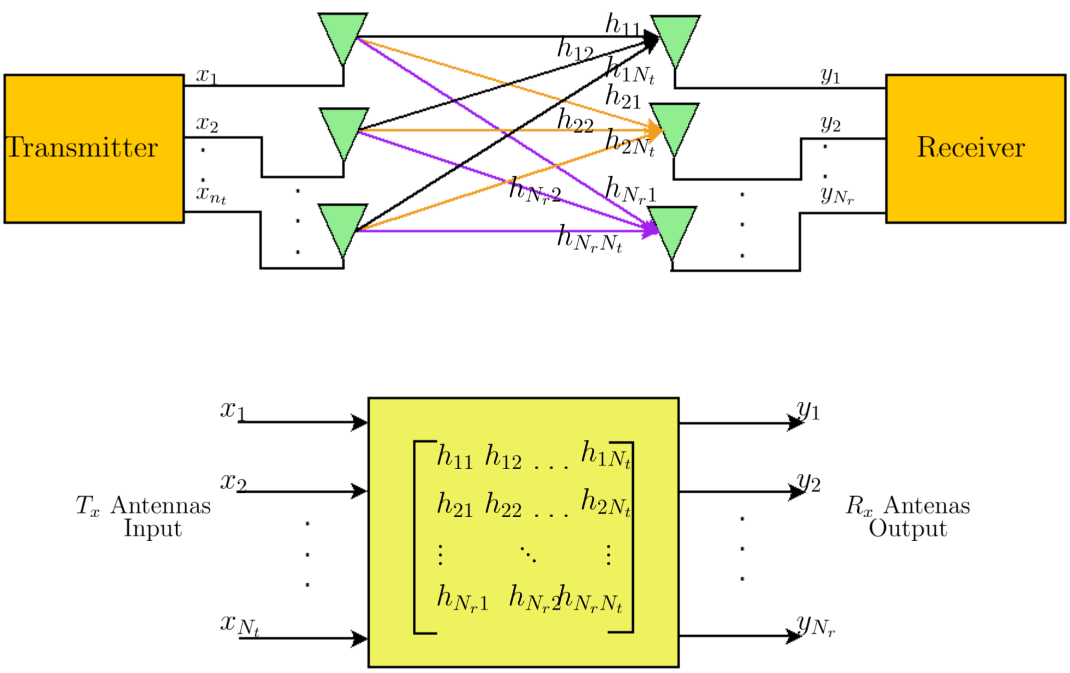


Figure 4.15: Block diagram of MIMO system

4.6 MIMO system-PAPR reduction

The concept of Multiple-Input and Multiple-Output (MIMO) was first vellicated by AR Kaye and DA George in 1970 [91]. MIMO is a technique employed to enhance the channel capacity of a wireless system using multiple transmit and receive antennas exploiting multipath propagation [92]. MIMO has become an essential element of wireless communication standards like IEEE 802.11n (Wi-Fi), IEEE 802.11ac (Wi-Fi), HSPA (3G), WiMAX (4G), and Long Term Evolution (4G). Recently, MIMO has been incorporated to power-line communication as part of ITU standard and HomePlug AV2 specification [93,94].

Block diagram of a MIMO system is presented in Figure 4.15. MIMO facilitates many type of diversity gains. To achieve these diversity gains, from signal processing perspectives of the system, operation of MIMO can be divided into three main categories such as precoding or beamforming, spatial multiplexing (SM), and diversity coding.

Precoding is a multi-stream beam-forming. In beam-forming, the same signal is transmitted from each of the transmit antennas with phase and gain weighting, such that the signal power is maximized at the receiver. The benefits of beam-forming is to increase the received signal gain - by making signals transmitted from different antennas add up constructively - resulting in reduced multipath fading effect.

In spatial multiplexing, a high-rate signal is split into multiple lower-rate streams and each stream is transmitted from a different transmit antenna in the same frequency channel. If these signals arrive at the receiver antenna array with sufficiently different spatial signatures and the receiver has accurate CSI, the receiver can separate these streams into (almost) parallel channels. Spatial multiplexing is a very powerful technique for increasing channel capacity at higher signal-to-noise ratios (SNR). The maximum number of spatial streams is limited by the number of transmitter and receiver antennas used. If N_t and N_r are the number of transmit and receiver antennas the number of spatial streams will be $min(N_t, N_r)$. Spatial multiplexing can be used without CSI at the transmitter, but can be combined with precoding if CSI is available. Spatial multiplexing can also be used for simultaneous transmission to multiple receivers, known as space-division multiple access or multi-user MIMO, in which case CSI is required at the transmitter [95].

Diversity coding techniques are used in absence of channel knowledge. In diversity methods, a single stream is transmitted and is coded using techniques called space-time coding. The signal is transmitted from each of the transmit antennas with full or near orthogonal coding. Diversity coding exploits the independent fading due to multiple antenna links to enhance signal diversity. Because, when there is no channel knowledge, there is no beam-forming or array gain from diversity coding. Diversity coding can be combined with spatial multiplexing, when some channel knowledge is available at the transmitter.

4.7 MIMO channel model

In MIMO systems, a transmitter sends multiple streams by multiple transmit antennas. The transmit streams go through a channel which consists of all $N_t N_r$ paths between the N_t transmit antennas and N_r receive antennas. The receiver gets the received signal vector by the multiple receive antennas and decodes the received signal vectors into the original information. A flat fading MIMO system can be modeled as

$$\mathbf{y} = \mathbf{H}\mathbf{x} + \mathbf{w} \tag{4.24}$$

Where $\mathbf{x}$ and $\mathbf{y}$ are transmitted and received signal vectors, respectively, and $\mathbf{H}$ and $\mathbf{w}$ are the channel matrix and the noise vector, respectively. x has a dimension of $N_t \times 1$, y has dimension of $N_r \times 1$ and H has the dimension of $N_r \times N_t$.

The ergodic channel capacity of MIMO systems in the presence of perfect instantaneous channel state information is given by [96]

$$\begin{aligned} C_{\mathrm{CSI_{perfect}}} &= E\left[\max_{\mathbf{Q};\,\mathrm{tr}(\mathbf{Q})\leq 1} \log_2 \det\left(\mathbf{I} + \rho\mathbf{H}\mathbf{Q}\mathbf{H}^H\right)\right] \\ &= E\left[\log_2 \det\left(\mathbf{I} + \rho\mathbf{\Sigma}\mathbf{S}\mathbf{\Sigma}\right)\right] \end{aligned} \tag{4.25}$$

where $(.)^H$ denotes Hermitian transpose, ρ is the ratio between transmit signal power and noise power, and $C_{CSI_{perfect}}$ is the capacity of the MIMO system when the perfect channel state information is available. Q the optimal signal covariance and is given by $\mathbf{Q} = \mathbf{V}\mathbf{S}\mathbf{V}^H$. Optimum value of Q is achieved through singular value decomposition of the channel matrix

$$\mathbf{H} = \mathbf{U}\mathbf{\Sigma}\mathbf{V}^H$$

and an optimal diagonal power allocation matrix

$$\mathbf{S} = \mathrm{diag}(s_1, \ldots, s_{\min(N_t,N_r)}, 0, \ldots, 0)$$

$tr(Q)$ is the trace of Q i.e addition of diagonal elements of Q, $\mathbf{U}$ is a $N_r \times N_r$ unitary matrix, $\mathbf{\Sigma}$ is a $N_r \times N_t$ diagonal matrix with non-negative real numbers on the diagonal and $\mathbf{V}$ is the $N_t \times N_t$ unitary matrix. The optimal power allocation is achieved through water-filling [97], and is given by

$$s_i = \left(\mu - \frac{1}{\rho d_i^2}\right)^+, \quad \text{for } i = 1, \ldots, \min(N_t, N_r)$$

where $d_1, \ldots, d_{\min(N_t,N_r)}$ are the diagonal elements of $\mathbf{\Sigma}$, $(\,\cdot\,)^+$ is zero if its argument is negative, and μ is selected such that $s_1 + \ldots + s_{\min(N_t,N_r)} = N_t$. $\mathbf{S}$ is the optimal diagonal power allocation matrix.

If the transmitter has only statistical channel state information, then the ergodic channel capacity will decrease as the signal covariance $\mathbf{Q}$ can only be optimized in terms of the average mutual information as [98,99]

$$C_{\mathrm{CSI}_{\mathrm{statistical}}} = \max_{\mathbf{Q}} E\left[\log_2 \det\left(\mathbf{I} + \rho \mathbf{H}\mathbf{Q}\mathbf{H}^H\right)\right]$$

Where $C_{\mathrm{CSI}_{\mathrm{statistical}}}$ is the channel capacity of the MIMO system when statistical channel state information is available. $\mathbf{I}$ is the identity matrix.

Spatial correlation of the channel has a strong impact on the ergodic channel capacity with statistical information.

If the transmitter has no channel state information it can select the signal covariance $\mathbf{Q}$ to maximize channel capacity under worst-case statistics, which means $\mathbf{Q} = \frac{1}{N_t}\mathbf{I}$ and accordingly

$$C_{\mathrm{no-CSI}} = E\left[\log_2 \det\left(\mathbf{I} + \frac{\rho}{N_t}\mathbf{H}\mathbf{H}^H\right)\right]$$

$C_{\mathrm{no-CSI}}$ is the channel capacity of the MIMO system when statistical channel state information is not available.

Depending on the statistical properties of the channel, the ergodic capacity is no greater than $\min(N_t, N_r)$ times larger than that of a SISO system.

To exploit the benefits offered by MIMO systems a diversity coding is employed. In this chapter a special type of Space Time Block Code (STBC), invented by Alamouti, is used. Details of the STBC coding is given in next section. Then the proposed SAS preprocessed DCT aided PAPR reduction method is extended to the STBC MIMO system.

4.8 Alamouti STBC coding

Alamouti invented the simplest of all the STBCs in 1998 [100]. It was first designed for a two-transmit antenna system and and is represented as a matrix:

$$C_2 = \begin{bmatrix} c_1 & c_2 \\ -c_2^* & c_1^* \end{bmatrix} \tag{4.26}$$

Where * denotes complex conjugate. c_1 andc_2 are the symbols to be transmitted at two different time instances by two antennas.

It takes two time-slots to transmit two symbols. In the first time slot, two symbols x_1 and x_2 (in parlance to OFDM) are transmitted simultaneously from two transmit antennas. During the second time slot, $-x_2^*$ is transmitted from first transmitter antenna and $x_1^*$is transmitted from second transmit antenna. The Alamouti encoder system for two transmit and two receive system is shown in Figure 4.16. Using the optimal decoding scheme discussed below, the bit-error rate (BER) of this STBC is equivalent to $2N_r$-branch maximal ratio combining (MRC). This is a result of the perfect orthogonality between the symbols after receive processing — there are two copies of each symbol transmitted and N_r copies received. Where N_r is the number of receiver antennas. This is a very special to STBC. It is the only orthogonal STBC

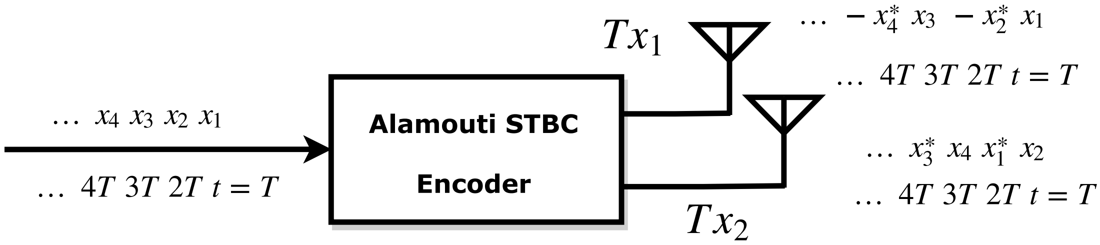


Figure 4.16: Alamouti encoder for 2×2 system

that achieves rate-1 [101]. That is to say that it is the only STBC that can achieve its full diversity gain without needing to sacrifice its data rate. Strictly, this is only true for complex modulation symbols. Since almost all constellation diagrams rely on complex numbers. However, this property usually gives Alamouti's code a significant advantage over the higher-order STBCs even though they achieve a better error-rate performance.

The significance of Alamouti's proposal in 1998 is that, it was the first demonstration of a method of encoding which enables full diversity with linear processing at the receiver. Earlier proposals for transmit diversity required processing schemes which scaled exponentially with the number of transmit antennas. Furthermore, it was the first open-loop transmit diversity technique which had this capability. Subsequent generalizations of Alamouti's concept have led to a tremendous impact on the wireless communications industry.

STBC codes for 3 transmit antennas scenario are:

$$C_{3,1/2} = \begin{bmatrix} c_1 & c_2 & c_3 \\ -c_2 & c_1 & -c_4 \\ -c_3 & c_4 & c_1 \\ -c_4 & -c_3 & c_2 \\ c_1^* & c_2^* & c_3^* \\ -c_2^* & c_1^* & -c_4^* \\ -c_3^* & c_4^* & c_1^* \\ -c_4^* & -c_3^* & c_2^* \end{bmatrix} \tag{4.27}$$

$$C_{3,3/4} = \begin{bmatrix} c_1 & c_2 & \frac{c_3}{\sqrt{2}} \\ -c_2^* & c_1^* & \frac{c_3}{\sqrt{2}} \\ \frac{c_3^*}{\sqrt{2}} & \frac{c_3^*}{\sqrt{2}} & \frac{(-c_1 - c_1^* + c_2 - c_2 *)}{2} \\ \frac{c_3^*}{\sqrt{2}} & -\frac{c_3^*}{\sqrt{2}} & \frac{(c_2 + c_2^* + c_1 - c_1^*)}{2}. \end{bmatrix} \tag{4.28}$$

STBC codes for 4 transmit antennas scenario are:

$$C_{4,1/2} = \begin{bmatrix} c_1 & c_2 & c_3 & c_4 \\ -c_2 & c_1 & -c_4 & c_3 \\ -c_3 & c_4 & c_1 & -c_2 \\ -c_4 & -c_3 & c_2 & c_1 \\ c_1^* & c_2^* & c_3^* & c_4^* \\ -c_2^* & c_1^* & -c_4^* & c_3^* \\ -c_3^* & c_4^* & c_1^* & -c_2^* \\ -c_4^* & -c_3^* & c_2^* & c_1^* \end{bmatrix} \tag{4.29}$$

$$C_{4,3/4} = \begin{bmatrix} c_1 & c_2 & \frac{c_3}{\sqrt{2}} & \frac{c_3}{\sqrt{2}} \\ -c_2^* & c_1^* & \frac{c_3}{\sqrt{2}} & -\frac{c_3}{\sqrt{2}} \\ \frac{c_3^*}{\sqrt{2}} & \frac{c_3^*}{\sqrt{2}} & \frac{(-c_1-c_1^*+c_2-c_2^*)}{2} & \frac{(-c_2-c_2^*+c_1-c_1^*)}{2} \\ \frac{c_3^*}{\sqrt{2}} & -\frac{c_3^*}{\sqrt{2}} & \frac{(c_2+c_2^*+c_1-c_1^*)}{2} & -\frac{(c_1+c_1^*+c_2-c_2^*)}{2} \end{bmatrix}. \tag{4.30}$$

Codes given in (4.27 and 4.28) achieve a rate of $\frac{1}{2}$ and $\frac{3}{4}$ respectively. Similarly, Codes given in (4.29 and 4.30) achieve a rate of $\frac{1}{2}$ and $\frac{3}{4}$ respectively. It can be noticed that only code in (4.26) achieves a rate of 1.

4.9 PAPR in MIMO OFDM systems

PAPR for a SISO channel was analyzed in section 4.2 of this chapter. From (4.10), the CCDF of a SISO communication system is given by

$$CCDF = 1 - (1 - e^{-z^2})^N$$

In MIMO OFDM scenario, $N_t \times N$ time domain samples are present. Hence, the CCDF for MIMO OFDM can be presented as [102].

$$\begin{aligned} CCDF_{MIMO} &= Pr(PAPR_{MIMO} < z_0) \\ &= 1 - (1 - e^{-z^2})^{N_t N} \end{aligned} \tag{4.31}$$

Where N_t is the number of transmitter antennas and N is the number of sub-carriers. Similarly, the CCDF under MIMO communication can be modified for the SLM and PTS techniques as analyzed in the preceding sections. In SLM the input signal is multiplied by a U number of phase vectors as discussed in the earlier section. So, the modified CCDF for MIMO OFDM using SLM PAPR reduction can be given by [102, Eq. (7)]

$$\begin{aligned} CCDF_{MIMOSLM} &= Pr(PAPR_{MIMOSLM} < z_0) \\ &= (1 - (1 - e^{-z^2})^{N_t N})^U \end{aligned} \tag{4.32}$$

With the same approach, the CCDF for MIMO OFDM using PTS PAPR reduction technique and using V number of phases is given by

$$\begin{aligned} CCDF_{MIMOPTS} &= Pr(PAPR_{MIMOPTS} < z_0) \\ &= (1 - (1 - e^{-z^2})^{N_t N})^V \end{aligned} \tag{4.33}$$

4.10 SAS preprocessed DCT aided PAPR reduction in MIMO

In this section the successive addition subtraction preprocessed DCT PAPR reduction is extended to MIMO case. The transmitter structure using the proposed algorithm is shown in Figure 4.17. The procedure is similar to the case described in section 4.4 for SISO system. The input bit stream is modulated with any signaling schemes like BPSK, QPSK, QAM etc. All symbols after modulation are coded according to STBC coding by taking account of number of transmit antennas to be used. For instance, if $N_t = 2$ STBC code in 4.26 is used. Similarly, for $N_t = 3$ STBC code in 4.27 or 4.28 is used and for $N_t = 4$ STBC code in 4.29 or 4.30 is used. Signals after STBC coding are processed in side the SAS block in similar fashion described in section 4.4. Signals available at output of SAS process are then subjected to serial to parallel conversion followed by N point DCT operation and IFFT operation as shown in Figure 4.17. After IFFT operation CP is added and converted back to parallel to serial data. Data are then grouped into 2, 3, or 4 symbols as per 4.26 to 4.30 depending on number of transmit antennas (N_t) used. These data are then transmitted through N_t number of antennas.

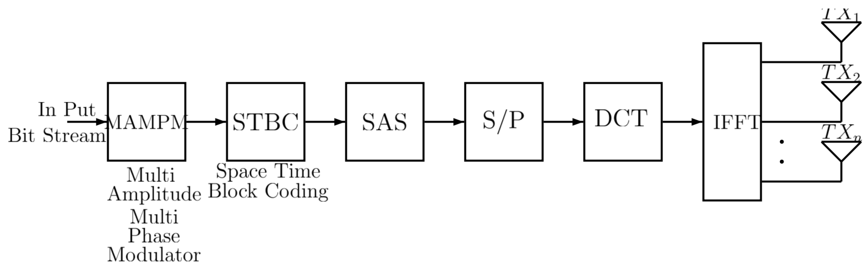


Figure 4.17: Transmitter for SAS Preproceed DCT aided PAPR reduction

4.11 Results and discussion

To evaluate the performance of the SAS preprocessed DCT aided PAPR reduction in MIMO systems simulation were carried out. Simultaneously, PTS and SLM techniques are also employed in the same studies. Performance of the proposed method was evaluated by varying number of sub-carriers, and by employing different number of transmit antennas. In all the simulations QPSK signaling is considered as modulation. Figure 4.18 to 4.20 shows the performance of PTS scheme for PAPR reduction in a 2, 3 and 4 transmit antennas scenarios respectively. All these systems employ 128 sub-carriers and QPSK modulation. The measured PAPR at a given CCDF of 0.01 is presented in table 4.3. Figure 4.18 portrays, the performance of PTS technique in 2 transmit antennas scenario. From the Figure, it is evident that the performance of

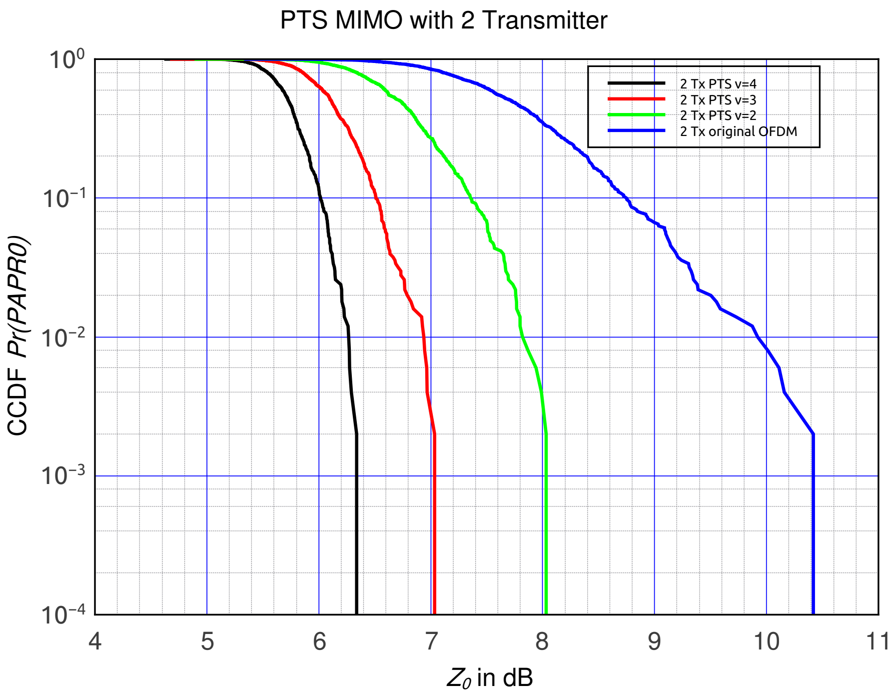


Figure 4.18: PAPR performance of 2 transmitter PTS scheme in MIMO OFDM system

Table 4.3: PTS at CCDF = 0.01, measured PAPR in dB

	Measured PAPR in dB			
No of Transmitter	V=2	V=3	V=4	Without PAPR
2 Tx	7.8	6.9	6.2	9.9
3 Tx	7.9	6.9	6.2	10.0
4 Tx	7.9	6.9	6.3	10.1

PTS algorithm improves as we go on increasing the number of sub-groups V. Similar performances were observed for the case of 3 and 4 transmit antennas scenarios. From Table 4.3 it can also be seen that PTS technique achieves a PAPR gain of 2.1, 2.9 and 3.6 dB from the original OFDM signal for 2, 3 and 4 number of sub-groups respectively in 2 transmit antennas scenario. Similarly, for 3 transmit antennas scenario shows an PAPR improvement of 2.1, 3.1 and 3.7 dB for V =2, 3, 4 number of sub-groups respectively. In 4 transmit antennas scenario, PAPR improvement of 2.1, 3.1, 3.8 dB was achieved for V = 2, 3, 4 number of sub-groups respectively.

Figure 4.21 to 4.23 shows the performance of SLM scheme for PAPR reduction in a 2,3 and 4 transmit antennas scenarios employing 128 sub-carriers with QAM-4 modulation.

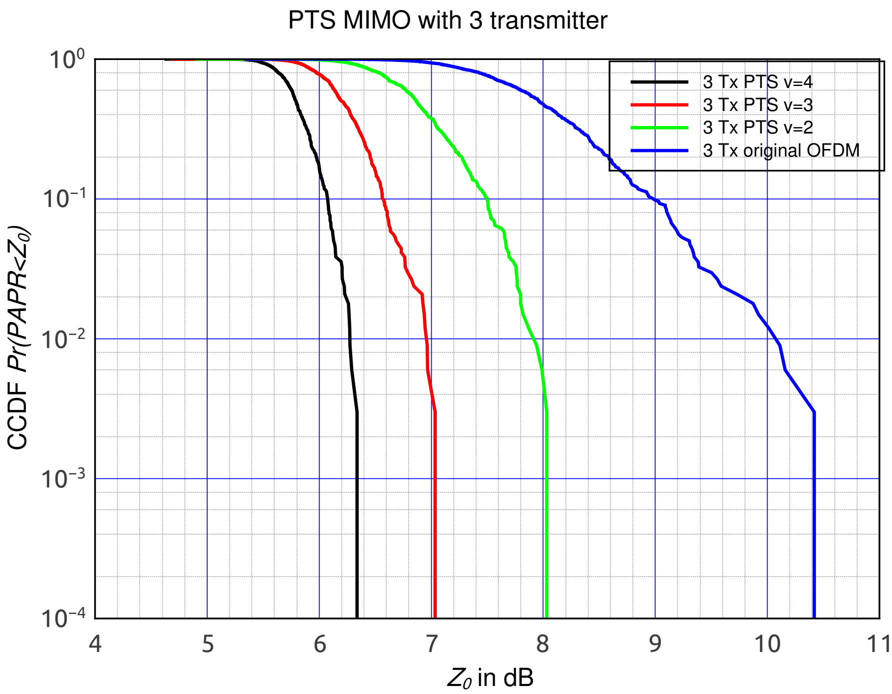


Figure 4.19: PAPR performance of 3 transmitter PTS scheme in MIMO OFDM system

The measured PAPR at a given CCDF of 0.01 is presented in table 4.4. Figure 4.21 presents the performance curve of SLM techniques in 2 transmit antennas scenario.

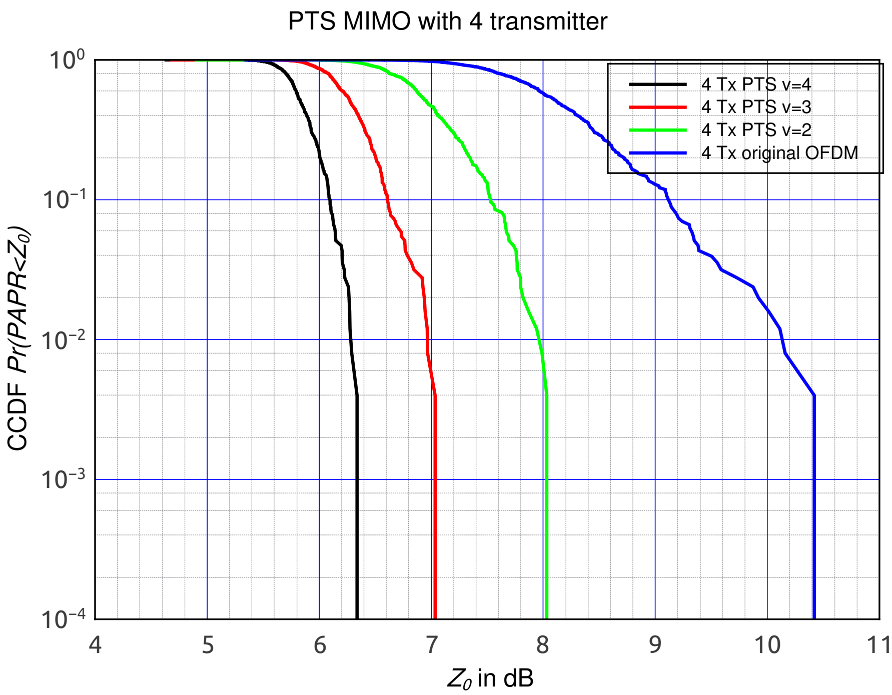


Figure 4.20: PAPR performance of 4 transmitter PTS scheme in MIMO OFDM system

Table 4.4: SLM at CCDF = 0.01, measured PAPR in dB

No of Transmitter	V=2	V=4	V=8	V=16	Original
2 Tx	8.6	7.7	7.1	6.7	9.8
3 Tx	8.8	7.8	7.2	6.7	9.9
4 Tx	8.8	7.8	7.2	6.7	10.1

From the Figure 4.21, it is evident that the performance of SLM algorithm improves as we go on increasing the number of sub-groups U. From Table 4.4 it can be observed that PAPR gain of 1.1, 2.1, 2.6, and 3.1 dB is achieved respectively for U=2, 4, 8, 16 in 2 transmit antennas case. 3 transmit antennas scenario exhibits PAPR gain of 1.1, 2.1, 2.7 and 3.2dB for U=2, 4, 8, 16 number of branches in SLM technique. PAPR gain of 1.2, 2.2, 2.8, and 3.3 are achieved for U=2, 4, 8, 16 number of branches respectively for 4 transmit antennas.

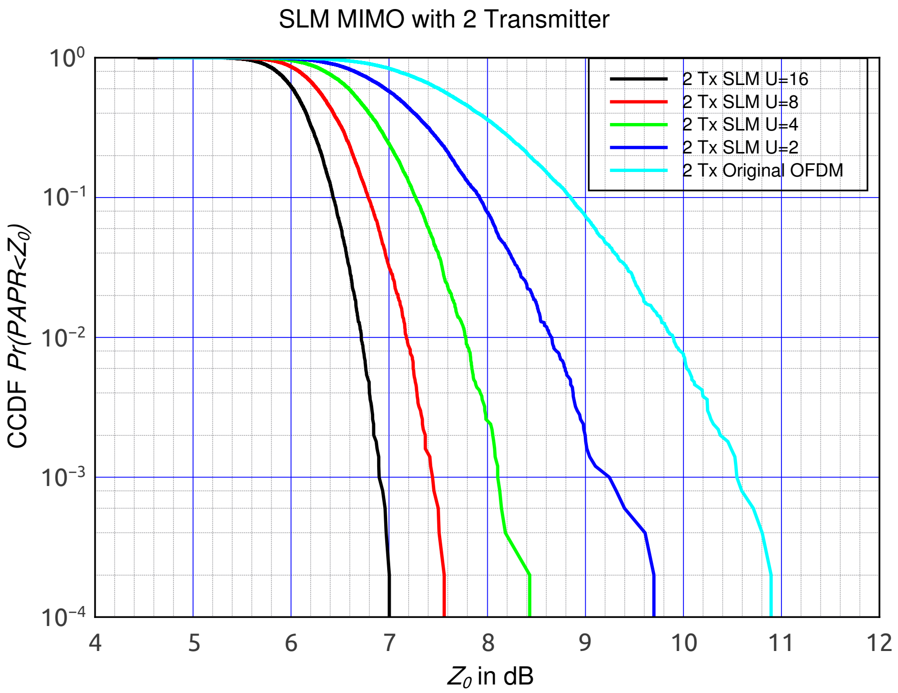


Figure 4.21: PAPR performance of 2 transmitter SLM scheme in MIMO OFDM system

From Table 4.3 and 4.4 it can be seen that PTS method of PAPR reduction outperforms SLM method.

Figure 4.24 and 4.25 reveals the performance of the proposed SAS method for PAPR

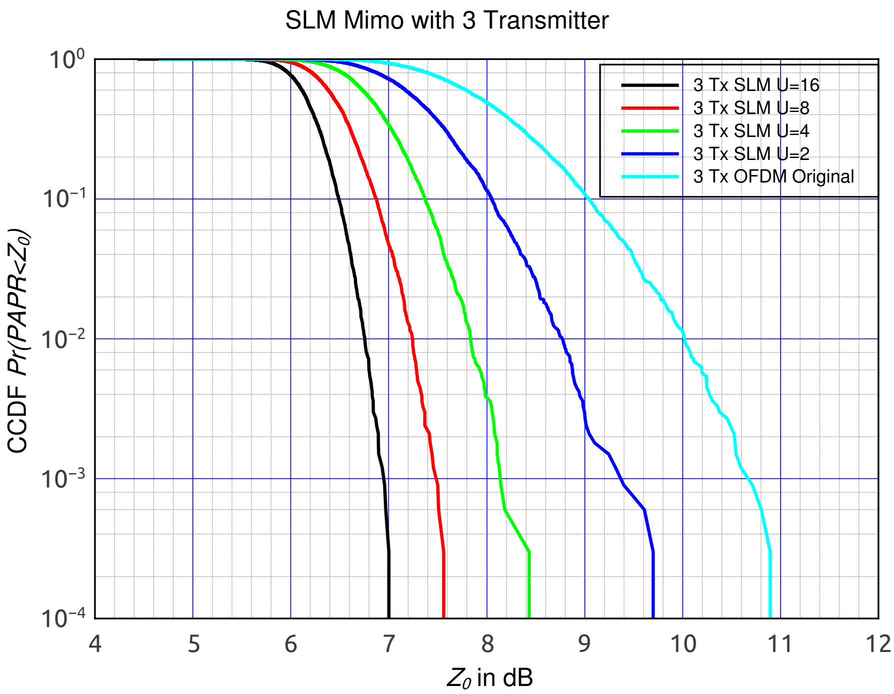


Figure 4.22: PAPR performance of 2 transmitter SLM scheme in MIMO OFDM system

reduction under different number of sub-carrier and transmit antennas. Measured PAPR at CCDF=0.01 is portrayed in the Table 4.5. This table follows that PAPR of

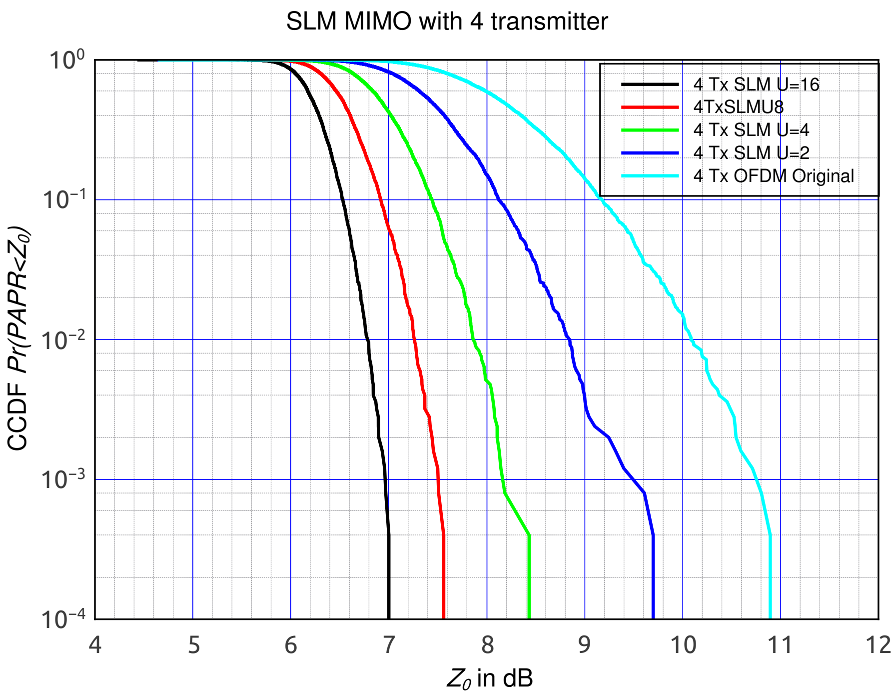


Figure 4.23: PAPR performance of 2 transmitter SLM scheme in MIMO OFDM system

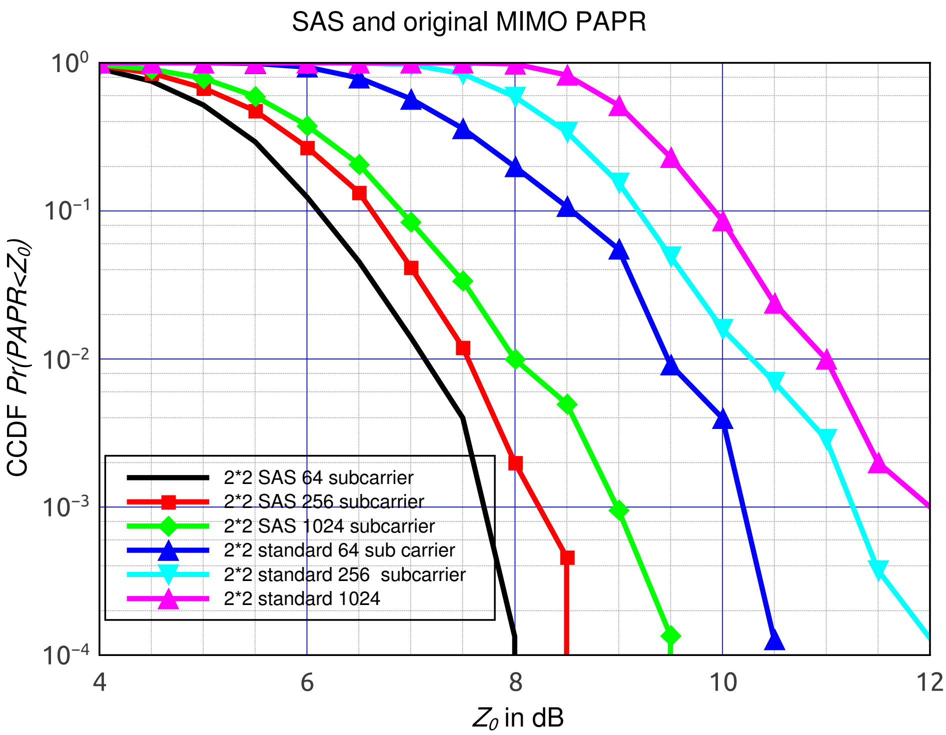


Figure 4.24: PAPR performance of SAS and Original OFDM in MIMO OFDM system

2.2, 2.7 and 2.9 dB gain is achieved by SAS method for 2 Tx scenario. PAPR gain of 2.1, 2.6 and 2.7 dB is achieved respectively for 64, 256 and 1024 sub-carriers in 3 transmit antennas case and a 2.6, 2.4 and 2.8 dB gain is achieved in case of 4 transmit antennas.

Figure 4.26 shows the performance comparison of different algorithms in STBC MIMO OFDM with 256 number of sub-carriers and QPSK signaling. Quantitative assessment

Table 4.5: SAS Performance measurement

		Measured PAPR in dB	
No. of Transmitter	No. of sub-carrier	SAS method	Original signal
2 Tx	64	7.1	9.3
	256	7.5	10.2
	1024	8.0	10.9
3 Tx	64	7.2	9.3
	256	7.6	10.2
	1024	8.3	11.1
4 Tx	64	7.6	10.2
	256	7.9	10.4
	1024	8.6	11.4

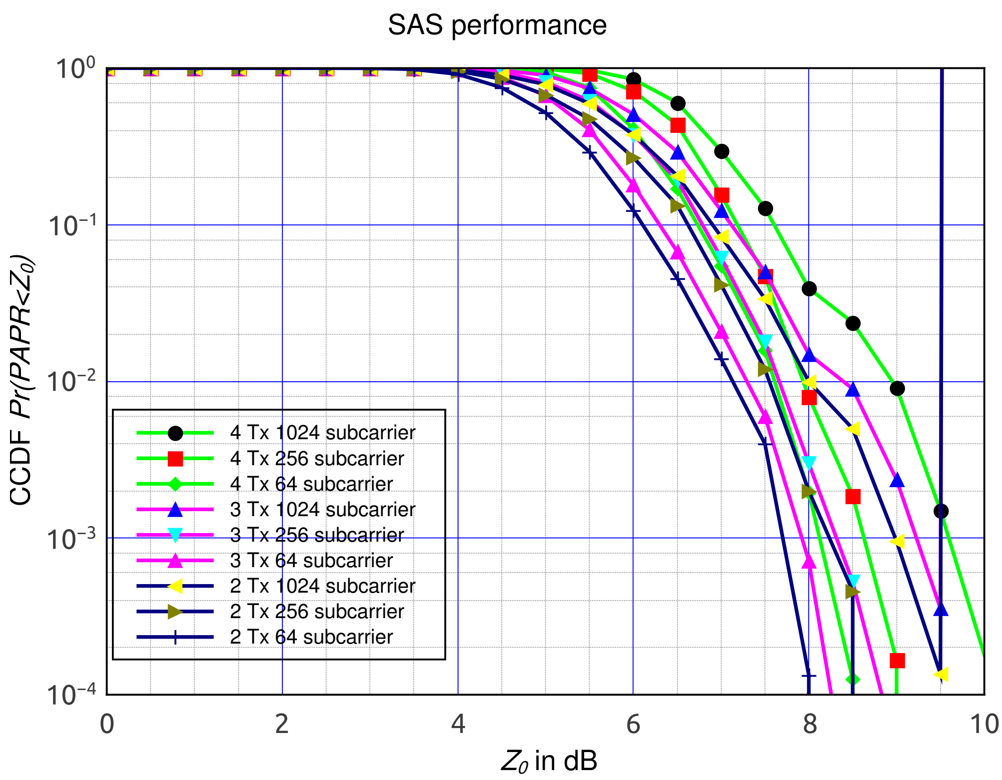


Figure 4.25: PAPR performance of SAS with number of transmitter in MIMO OFDM system

Table 4.6: Measured PAPR using different techniques at CCDF=.01

Original	SLM technique				SAS Technique	PTS Technique		
	U=2	U=4	U=8	U=16		V=2	V=3	V=4
10.2	9.1	8.2	7.7	7.2	7.5	8.4	7.5	6.9

of Figure 4.26 is outlined in Table 4.6 at CCDF of 0.01. Table 4.6 reveals that the performance of proposed SAS algorithm is better than the SLM with U=2, 4, 8 and PTS with V=2. However, SLM with U=16 and PTS with V=4 outperforms to the proposed SAS method. Furthermore, PTS with V=3 gives approximately same result as of SAS method. From Table 4.6 it is seen that proposed SAS method achieves PAPR gain of 2.6 dB from original OFDM signal without PAPR reduction. Moreover, it gains performance improvement of 1.5 dB, 0.6 dB, 0.1 dB and 0.9 dB as compared to SLM with U= 2, 4, 8 and PTS with V=2 respectively. For PTS with V=4, the performance difference is merely 0.0 dB in favor of PTS. SLM with U=16 has improvement of 0.2 db and PTS with V= 4 has improvement of 0.6 dB over proposed SAS method.

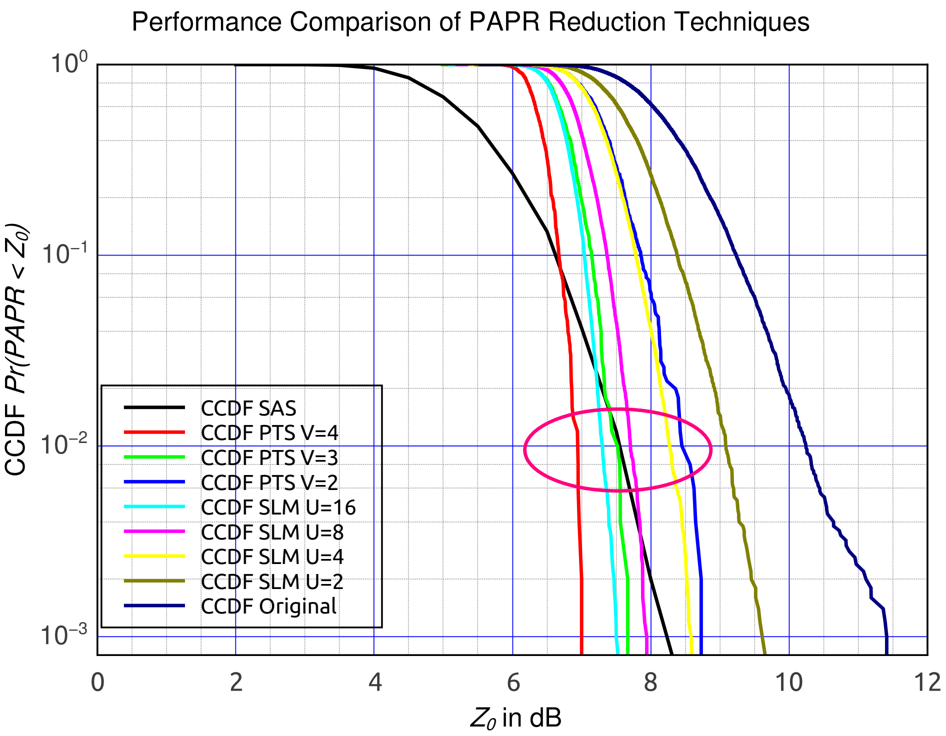


Figure 4.26: PAPR performance comparison of SAS method with PTS and SLM method in MIMO OFDM system employing 256 sub-carrier

4.11.1 Computational complexity issues of different algorithms

From the above findings, it is observed that the performance of PTS technique improves by increasing the number of sub-blocks and the performance of SLM technique improves by increasing number of phase vectors. The proposed algorithm is not based on any partitioning method. Computational complexity of all the PAPR reduction techniques, however, is dependent on the number of sub-carriers used. Each of the method also undergoes the process of IFFT. Hence, at this point the computational complexity can be divided into two parts. First part deals with the preprocessing computational complexity and the second deals with the number computation required in IFFT stage. Then, a generalized formula for N_t number of transmit antennas; for MIMO case; can be derived. Without loss of ambiguity, it is assumed $N = 64, 128, 256, \ldots$ is the number of sub-carriers and $M = 2, 4, 8, 16, \ldots$ is the signaling constellation. Total complexity of different techniques were attributed in Table 4.7. However, preprocessing complexity of different algorithms are as follows:

PTS method

In this scheme the data stream is divided into V number of sub-blocks. Each sub-block is multiplied with a phase. W is the number signaling points chosen from M number of constellation points. Each sub-block is multiplied with a phase factor to optimize the PAPR. Hence, there is NW^{V-1} complex multiplications.

SLM method

The OFDM signal is multiplied by U number of phase vectors. Each phase vector contains N number of phases. So there is UN number of complex multiplications.

SAS Method

This method deals with addition and subtraction of symbols. From (4.17) it is clear that there is N number of additions only. Furthermore, DCT requires $Nlog_2N$ multiplications and N number of additions.

4.11.1.1 Complexity in IFFT process:

For N point IFFT, it requires $\frac{N}{2}log_2N$ number of complex multiplications and $Nlog_2N$ number of additions. Here, computational complexity of different algorithms at IFFT stage is critical in terms of computational complexity analysis.

PTS method

V number of sub-block data are to be processed in IFFT. Hence, $V\frac{N}{2}log_2N$ of multiplications and $VNlog_2N$ number of additions are required.

SLM method

U number of OFDM symbols each carrying N data points are to be processed in IFFT. Hence, $U\frac{N}{2}log_2N$ of multiplications and $UNlog_2N$ number of additions are required.

SAS Method

From the Figure 4.17 it is seen that SAS preprocessed method uses only a single

Table 4.7: Computational complexity of different PAPR reduction algorithms in N_t transmitter antenna

Method	Multiplications	Additions
PTS	$N_tNW^{V-1} + N_tV\frac{N}{2}log_2N$	N_tVNlog_2N
SLM	$N_tUN + N_tU\frac{N}{2}log_2N$	N_tUNlog_2N
SAS	$N_t\frac{N}{2}log_2N + N_tNlog_2N$	$(N + Nlog_2N)N_t$

OFDM block. The OFDM symbol is to be processed once for a OFDM symbol to be transmitted. So, $\frac{N}{2}log_2N$ of multiplications and $Nlog_2N$ number of additions are required.

Based on above analysis computational complexity of different algorithms are presented in Table 4.7.

It is very common that IFFT is inevitable in OFDM and so in PAPR reduction. So, depending on the PAPR reduction method computational complexity varies. Here,it is important to see the complexity of different algorithms at preprocessing step that is discussed above.

4.12 Summary

In this chapter PAPR reduction of OFDM system in SISO and MIMO systems was discussed. A brief literature survey on PAPR reduction for OFDM was presented. CCDF was derived for both SISO and MIMO cases. In SISO OFDM, PTS and SLM techniques were discussed in detail. The proposed SAS preprocessed DCT based PAPR reduction method was analyzed. For SISO, a detailed performance analysis for different methods was carried out. Computational complexity associated with each of the algorithm was also carried out. Subsequently the proposed technique was extended for plausible PAPR reduction in MIMO OFDM system. An extensive simulation work for different number of transmit antennas was performed. The performance of the proposed algorithm was compared with standard techniques like PTS and SLM technique for different number of transmit antennas. It was observed that the proposed method performs better than others.

5

Evolutionary estimation techniques to Multi user detection in SDMA OFDM system

"God helps those who do not help themselves."

Swami Vivekananda

Contents

This chapter presents a brief discussion on space division multiple access (SDMA) which facilitates multi users to communicate over a common bandwidth. Use of evolutionary computing based algorithm to fine tune the multi user detection MMSE filter is presented. Widely used Genetic Algorithm is also discussed for its application in SDMA. Subsequently an evolutionary algorithm called Bat algorithm is presented. A comparative analysis performance of GA based SDMA and Bat algorithm aided SDMA is presented. Performance analysis shows that Bat algorithm aided SDMA provides marginal gain over GA aided SDMA.

5.1 Introduction to SDMA

SDMA (Space-Division Multiple Access or Spatial Division Multiple Access) is a MIMO based wireless communication network architecture. SDMA architecture can be reconfigured and rolled out for most of the well-known mobile communication architectures such as CDMA, TDMA and FDMA. It is seen that SDMA is a subclass of MIMO arrangement facilitating multiple spatially (geographically different locations) separated users to communicate over a shared communication channel sharing the same bandwidth. SDMA has been one of the promising candidate to solve the capacity problem in wireless communication system. The exploitation of spatial dimension, called spatial signature, enables to identify individual users irrespective of their overlap in time/frequency/code domains and hence result in increased system capacity. Few of the major contributions by different researchers in this field are listed in Table 5.1

Table 5.1: Major contribution to SDMA

Year	Author(s)	Contribution
1982	Yeh and Reudink [103]	Proposed to achieve spectrum efficiency in wireless system using modest number of space diversity.
1983	Ko and Davis [104]	Use of SDMA in context of satellite communication networks.
1994	Xu *et al.* [105]	Experimental studies on SDMA systems.
1997	Liu and Xu [106]	Addressed uplink blind channel estimation in SDMA.
1998	Tsoulos *et al.* [43,107]	Demonstrated both transmit and receive beam-forming in SDMA user access.
1999	Vandenameele *et al.* [108–110]	Advocated combined SDMA-OFDM approach that gains advantages of both techniques.
2001	Shad *et al.* [111]	Proposed dynamic slot allocation in packet switched SDMA system.
2002	Fang [112]	Investigated performance analysis of resource allocation schemes for SDMA system
	Oechtering [113]	Investigated CDF of the uplink carrier to interference ratio in mobile radio network.
2003	Thoen *et al.* [114]	Proposed Constrained Least Square (CLS) in receiver of multi-user SDMA system
	Hanzo *et al.* [115]	A brief elaboration of channel estimation and multi user detection techniques for SDMA-OFDM system.

Continued on next page

Table 5.1 – continued from previous page

Year	Author(s)	Contribution
2004	Spencer *et al.* [116]	Proposed to constrained solution like block diagonalization and successive optimization schemes for downlink SDMA system.
2005	Dai [117]	Analysed CFO estimation in SDMA-OFDM system.
2006	Hanzo *et al.* [46]	Propose a hybrid multi user detection scheme using Genetic algorithm.
2010	Jingon and Sayed [118]	Investigated an optimal scheduling method that maximises the sum rate in two ray relay model using SDMA.
2010	Dahman *et al.* [119]	Proposed a novel transmission technique for MIMO broadcasting directional channels, called the Angle-of-Departure-Aided Opportunistic Space-Division Multiple Access (AOD-OSDMA) technique.
2013	Bagadi and Das [44]	Carried out an adaptive multiuser detection (MUD) technique using the complex radial basis function (CRBF) network SDMA-OFDM system
2015	Chong *et al.* [120]	Proposed a novel SDMA method by using the multibeam characteristic of the time-modulated array (TMA). The TMA generates the fundamental and harmonic components pointing to different directions.

SDMA-OFDM is currently a challenging field. Experimental study of SDMA was carried out by Xu *et al.* [105]. Vandenameele first time proposed the combination of SDMA and OFDM [108]. Many researches have been carried out for different field of SDMA-OFDM. However, multi user detection in SDMA-OFDM is an intersting research for past few years. Few of the most mile stone contributions by different researchers were given in Table 5.1.

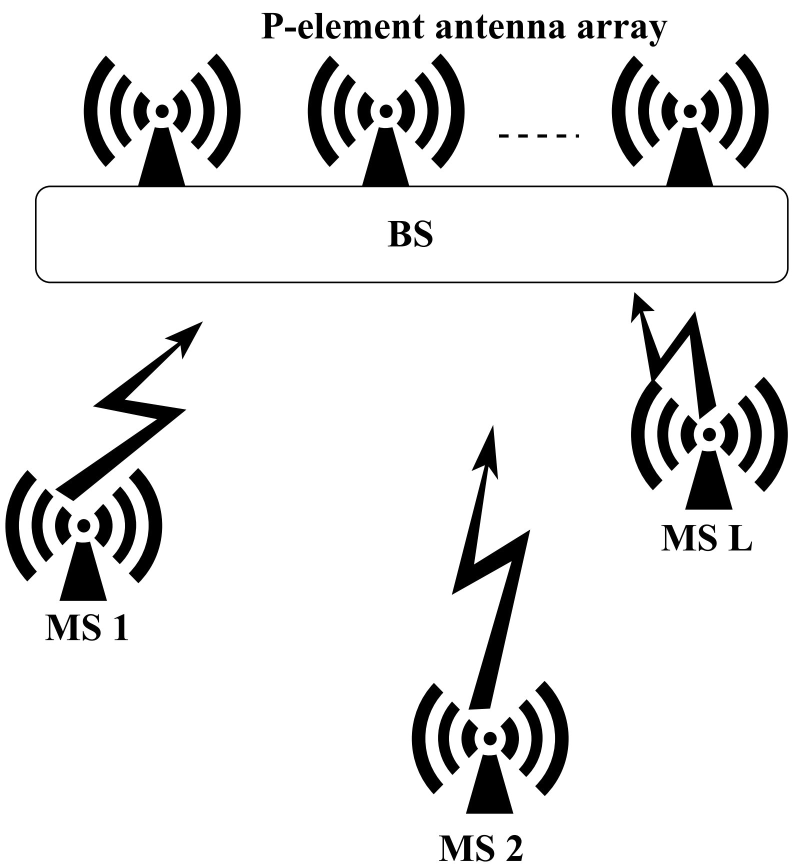


Figure 5.1: A generic SDMA system of P-element receiver antenna supporting L mobile users

The concept of SDMA is illustrated in Figure 5.1. The scenario presented in As depicted in the Figure 5.1is an uplink system. 5.1, each user exploits a single transmitter antenna at the Mobile Station (MS) and simultaneously communicates with the Base Station (BS) equipped with an array of receiving antennas. More specifically, SDMA is a special class of MIMO family, where transmission of multiple antenna can not be coordinated.

This is because each user is allocated a transmitter antenna independently. Few of the advantage that SDMA offers are [121] as follows:

- **Range extension:** Use of large antenna array increases the coverage area compared to single antenna scenario. Number of cells to cover a geographic area can be significantly reduced.

- **Multi-path mitigation:** The use of MIMO architecture in SDMA effectively mitigates the multi-path propagation. Moreover, in many scenarios multipath phenomenon can be exploited to enhance desired users signal by employing efficient receiver diversity schemes.

- **Capacity increase:** SDMA can be used in any multiple access standard at the cost of limited increase in system complexity with substantial increase in channel capacity.

- **Interference suppression:** The interference introduced by other users in other cells can be significantly reduced by exploiting the desired user's unique user specific channel impulse response.

- **Compatibility:** SDMA is compatible with most of the existing modulation schemes, carrier frequency and other specifications. It can be implemented using various array geometries and antenna types.

The combination of SDMA and OFDM results in SDMA-OFDM system [108–110,114, 115,117,122–124] that exploit the merit of both SDMA and OFDM.

Figure 5.2 shows a satellite system that uses spatial division multiple access (SDMA) technology. In this example, a single satellite contains several directional antennas. Some of these antennas use the same frequency. This allows a single satellite to simultaneously communicate with multiple earth station that operate on the same frequency . Usually beams that are separated by more than two or three half-power bandwidths and can use the same frequencies. This example is a satellite

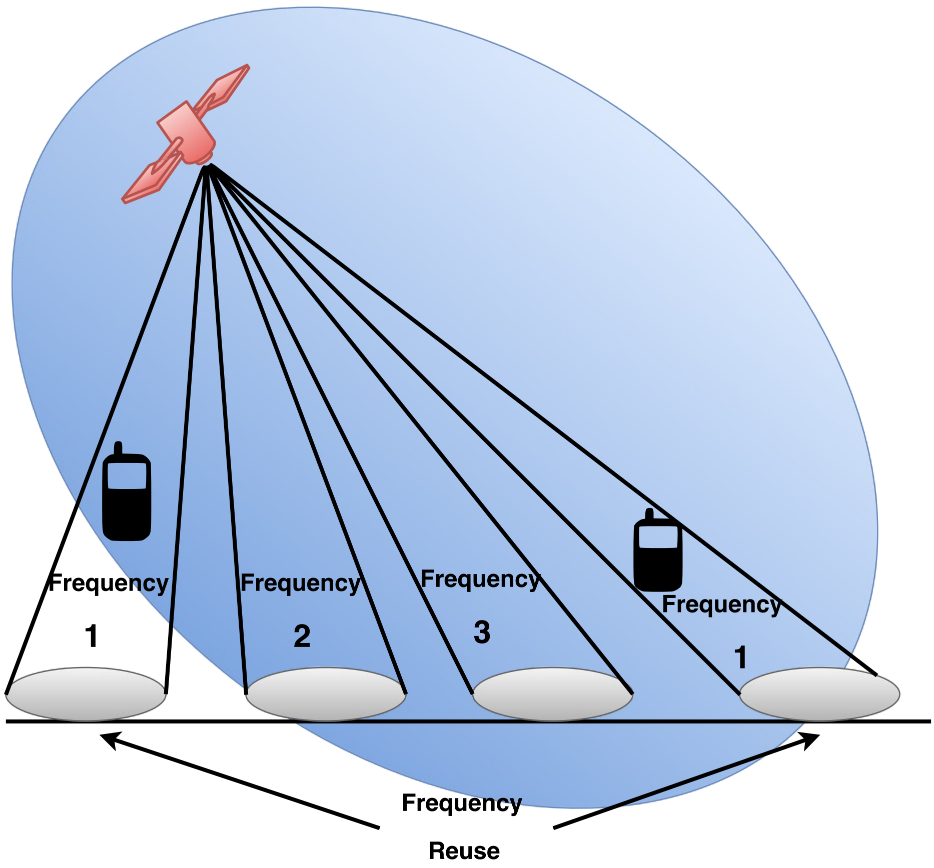


Figure 5.2: A satellite communication system using SDMA architecture.

communications mode that optimizes the use of radio spectrum and minimizes system cost by taking advantage of the directional properties of dish antennas. In SDMA, also known as SDM (spatial-division multiplex), satellite dish antennas transmit signals to numerous zones on the earth's surface. The antennas are highly directional, allowing duplicate frequencies to be used for multiple surface zones.

5.2 MIMO-SDMA-OFDM Description

Though OFDM can easily mitigate the multipath effect, it can not enhance the channel capacity. To increase the channel capacity, diversity gain of MIMO can be employed to OFDM leading MIMO-OFDM technology. The technology can be enhanced to accommodate multiple users through space diversity of MIMO called MIMO-SDMA-OFDM system or simply SDMA-OFDM system.

5.2.1 MIMO Channel Model

The Figure 5.3 presents an MIMO-SDMA uplink system. In this figure L number of users transmit the signal over same bandwidth by employing L number of transmit antennas. Each user is assigned a transmitter antenna and hence L number of transmit antennas are used. In the receiver section, P number of receiver antennas are present. Without loss of generality, N_t is the number of transmitter and N_r is the number of receiver antenna. Hence, in this example a MIMO wireless communication channel is constituted by $(N_r \times N_t)$ communication links. Each of the corresponding $(N_r \times N_t)$ SISO propagation links comprises a multiplicity of statistically independent components, termed paths. Thus, each of these SISO propagation links can be characterized as a multi-path SISO channel. The multi-carrier SDM-OFDM structure transceiver allows to characterize the broadband frequency-selective channel considered as an OFDM sub-carrier-related vector of flat-fading Channel Transfer Function (CTF) coefficients, where, for each OFDM symbol n and sub-carrier k the MIMO channel is characterized by an $(N_r \times N_t)$-dimensional matrix $H[n, k]$ of the CTF coefficients associated with the different propagation links, in such way that the element $H_{ij}[n, k]$ of the CTF matrix $H[n, k]$ corresponds to the propagation link connecting the jth transmit and ith receive antennas [126].

In SISO, the cross-correlation function $r_H[m, l]$, which characterized both the time and frequency-domain correlation properties of the discrete CTF coefficients $H[n, k]$

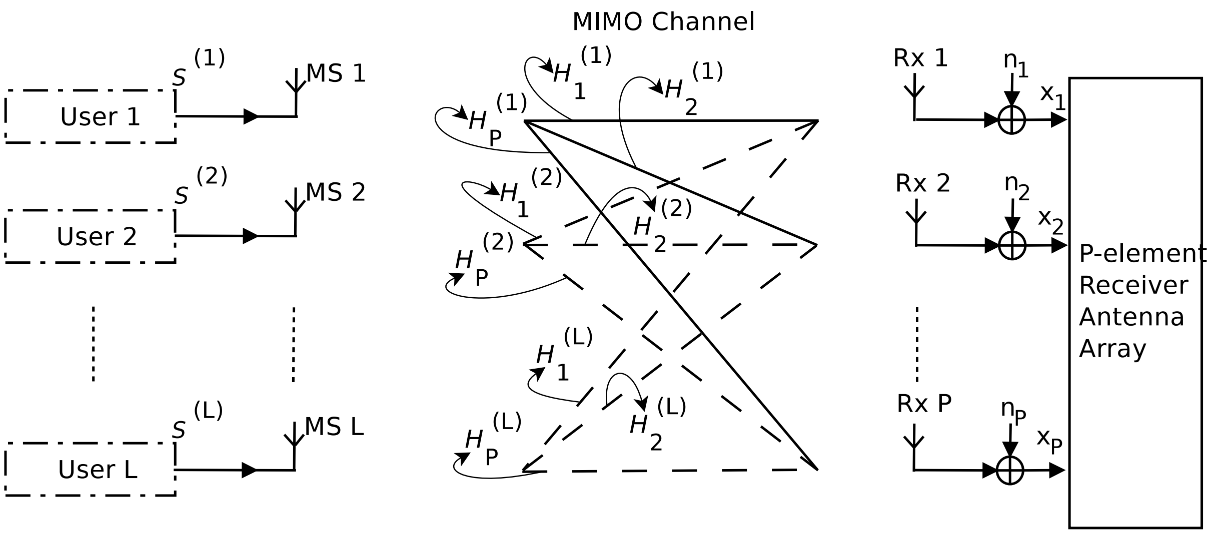


Figure 5.3: MIMO-SDMA Uplink channel

associated with different OFDM blocks and sub-carriers, can be described as [126,127]

$$\begin{aligned} r_H[m,l] &= E\{H[n+m,k+l]H^*[n,k]\} \\ &= \sigma_H^2 r_t[m] r_f[l] \end{aligned} \tag{5.1}$$

where $r_t[m]$ and $r_f[l]$ are the time-domain correlation function and frequency-domain correlation function described by [126,128]

$$r_t[m] = \frac{\sin(2\pi f_D m)}{2\pi f_D m}$$

,

and

$$r_f[l] = |C(l\Delta f)|^2 \sum_{i=1}^{L} \frac{\sigma_i^2}{\sigma_H^2} e^{-j2\pi l\Delta f \tau_i}$$

where

$$\sigma_H^2 = \sum_{i=1}^{L} \sigma_i^2$$

where $C(f)$ is the frequency response of the pulse-shaping filter employed by the particular system, σ_i^2 and $\tau_i, i = 1, ..., L$, are the average power and the corresponding delay of the L-tap PDP encountered, while σ_h^2 is the average power per MIMO channel link.

Hence, cross correlation function $r_{H_{ij}}[m, l]$associated with particular (i,j)th propagation link of MIMO channel, as well as different OFDM symbol and sub-carrier indices n and k can be described as

$$\begin{aligned} r_{H_{ij}}[m,l] &= E\{H_{ij}[n+m,k+l]H_{ij}^*[n,k]\} \\ &= \sigma_H^2 r_t[m] r_f[l] \end{aligned} \tag{5.2}$$

Here (5.2) is derived assuming different MIMO channel links are mutually uncorrelated. This assumption is valid under the condition that the spacing between two adjacent antenna are separated by $\lambda/2$, where λ is the wave length corresponding to RF signal employed. The overall cross correlation function between the (i, j)th and (i', j')th propagation link can be expressed as

$$\begin{aligned} r_{H_{ij}}[m,l] &= E\{H_{ij}[n+m,k+l]H_{ij}^*[n,k]\} \\ &= \sigma_H^2 r_t[m] r_f[l] \end{aligned} \tag{5.3}$$

5.2.2 SDMA MIMO Channel Model

Figure 5.3 shows an SDMA uplink MIMO channel model. Each of the N_t mobile users employs a single transmitter antenna at the Mobile Station (MS), while the BS's receiver exploits N_r antennas. At the kth sub-carrier of the nth OFDM symbol received by the N_r-element receiver antenna array we receive the complex received signal vector $x[n, k]$, that is constituted by the superposition of the independently faded signals associated with the L mobile users and contaminated by AWGN are expressed as [126]

$$\mathbf{x} = \mathbf{HS} + \mathbf{w} \tag{5.4}$$

where $\mathbf{s}$ is a $(N_t \times 1)$ dimensional transmit signal vector, $\mathbf{x}$ is a $(N_r \times 1)$ dimensional received signal vector and w is the $(N_r \times 1)$ dimensional noise vector. Here, the indices $([n, k])$ have been omitted for each vector for the sake of notational convenience. The vectors x, $\mathbf{s}$ and $\mathbf{n}$ are given by

$$\mathbf{x} = [x^1, x^2, ..., x^{N_r}]^T \tag{5.5}$$

$$\mathbf{S} = [s^{(1)}, s^{(2)}, ..., s^{(N_t)}]^T \tag{5.6}$$

$$\mathbf{w} = [w^1, w^2, ..., w^{N_r}]^T \tag{5.7}$$

The $(P \times L)$ dimensional Frequency-Domain Channel Transfer Functions (FD-CHTFs) matrix H containing L number of users, is given by

$$\mathbf{H} = [\mathbf{H^{(1)}}, \mathbf{H^{(2)}}, ..., \mathbf{H^{(N_t)}}] \tag{5.8}$$

where $\mathbf{H^{(l)}}$ for $l = 1, 2, \ldots, N_t$ is the frequency domain channel transfer function . This is associated with lth user's transmitter antenna to each of the N_r element receiver antenna transmission path. Hence this can be expressed as

$$\mathbf{H}^{(\mathbf{l})} = [\mathbf{H_1^{(l)}}, \mathbf{H_2^{(l)}}, ..., \mathbf{H_{N_r}^{(l)}}] \tag{5.9}$$

(5.4) to (5.9) are based on few assumptions. We assumed that the signal $\mathbf{s}^{(\mathbf{l})}$ is transmitted by lth user has zero mean and variance σ_l^2. The AWGN noise signal has zero mean and variance of σ_w^2. Each of the receiver or users are independent, stationary and complex distributed processes with zero mean and unit variance.

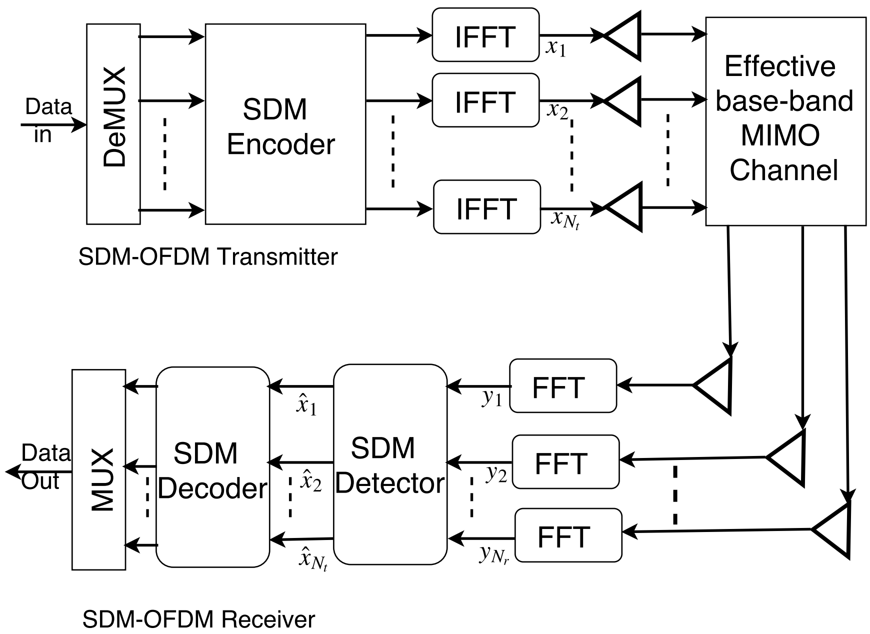


Figure 5.4: Generic SDM-OFDM transceiver

5.2.3 SDM-OFDM Transceiver structure

The structure of a generic baseband SDM-OFDM system is depicted in Figure 5.4. The received signal, $y_i[n,k]$ can be presented as

$$y_i[n,k] = \sum_{j=1}^{N_t} H_{ij}[n,k]x_j[n,k] + w_i[n,k] \tag{5.10}$$

where $i = 1, 2 \ldots N_r$ are receiver antenna, $n = 1, 2, \ldots$ are the OFDM symbols and $k = 0, 1, \ldots K-1$ are sub-carrier indices. $y_i[n,k]$, $x_j[n,k]$ and $y_i[n,k]$ denote received signal at ith received antenna, transmitted symbol from jth transmit antenna and Gaussian noise sample added at ith receiving antenna. $H_{ij}[n,k]$ is the complex-valued CTF coefficient associated with the propagation link between the jth transmit and ith receive antennas at the kth OFDM sub-carrier at the time instance n.

The SDM-OFDM system model described by (5.10) can be represented in vector form as

$$y[n,k] = H[n,k]x[n,k] + w[n,k] \tag{5.11}$$

5.3 SDMA-OFDM Detectors

In a communication system received signal is processed for its detection at the receiver. In an uplink scenario the detector receives the signal and estimates it by employing different type of algorithms such as MMSE, ML, etc. These detectors are classified into linear and nonlinear detector depending on their working principle and mathematics involved.

5.3.1 Linear Detectors

Linear detectors combines the signal from each receiver antenna linearly and estimate transmitted symbols of each user with the help of a transformation of the received vector by x given as below.

$$\hat{g}_l = z_l^* x \tag{5.12}$$

Using the value of x from (5.4)

$$\hat{g}_l = \mathbf{z_l^*HS} + \mathbf{z_l^*w} \tag{5.13}$$

Where $(*)$ stands for conjugate transpose, z_l for $l = 1, 2, \ldots, N_t$ is the lth column of weight matrix of $\mathbf{Z}$. Here it can be noted that the dimension of $\mathbf{Z}$ is $N_r \times N_t$. If $\Re$ denotes the real part, then estimate of the transmitted symbol is

$$\hat{s}^l = sign \ \Re \ \{\hat{g}_l\} \tag{5.14}$$

The weight matrix $\mathbf{Z}$ can be estimated with zero forcing [129], MMSE [45] and other techniques.

Zero Forcing Detectors

This type of detector attempts to null out the interference by inverting the channel and is defined as

$$\hat{S}^l = \mathbf{H}^+\mathbf{x} \tag{5.15}$$

where H^+ is the Moore-Penrose pseudo-inverse.

Minimum Mean Square Error Detectors

MMSE detector attempts to reduces the combined effect of interference between the parallel channels and additive Gaussian noise. It's performance is slightly better than ZF receiver. On the down side, it can not exploit the channel diversity. MMSE design attempts to minimize the mean squared error only.

The weight vector for MMSE can be represented by [45,129,130]

$$\mathbf{Z_{MMSE}} = (\mathbf{HH}^* + \sigma_\mathbf{w}\mathbf{I})^{-\mathbf{1}}\mathbf{H} \tag{5.16}$$

where σ_w is the noise variance, $\mathbf{H}^*$ conjugate of the frequency domain channel transfer function and σ_w is the noise variance.

5.3.2 Nonlinear Detectors

Multiuser detection is closely related to equalization for inter symbol interference (ISI) channels. The decorrelating detector is analogous to the zero-forcing equalizer and MMSE linear multiuser detector is the multidimensional version of the MMSE linear equalizer for the single-user IS1 channel. However, the linear structure of these detectors often limits their performance [131]. Hence, nonlinear detectors can enhance the performance by increasing the search space.

Maximum Likelihood Detectors

Maximum Likelihood (ML) is the optimum detector that enumerates on each sub-carrier of all possible combinations of transmitted symbols [130,132,133]. It maximizes the chance of getting true symbol by minimizing the Euclidean distance between the actual received symbol and the symbol that would be received if that particular combination would have been transmitted. It retains those symbols which provides the minimum Euclidean distance. The algorithm is presented as follows:

$$\hat{\mathbf{S}} = \arg \min_{N_t} ||\mathbf{x} - \mathbf{HS}^{\mathbb{C}}||^{\mathbf{2}} \tag{5.17}$$

where $\mathbb{C}$ is the complete search space, N_t is the number of transmitters, H is the frequency domain channel transfer function $\mathbf{x}$ is the received signal vector and $S^{\mathbb{C}}$ is the complete search space $\mathbf{S}$.

VBLAST encoder and decoder

Vertical-Bell Laboratories Layered Space-Time (VBLAST) is a popular detection algorithm to receive the signal from multi-antenna MIMO systems. V-BLAST algorithm works in three steps: ordering, interference cancellation, and interference nulling [45,134]. It is a vertically layered coding structure, in which independent code blocks (called layers) are associated with a particular transmit antenna.

At first, the algorithm decodes the strongest user's signal from all the received signals. The effect of this detected signal in all other received equations is canceled. Subsequently, it finds the best estimate of a signal from the updated equations. This is called interference nulling. The algorithm continues recursively by canceling the effects of the detected signals until last user's signal is detected.

The algorithm can be described as follows [41,134,135]. Given that a set $\mathbf{M}$ be an ordered set that contains the order in which the components of the transmitted vector $\mathbf{S}$ are to be extracted. M can be given by

$$\mathbf{M} = \{\mathbf{m_1}, \mathbf{m_2}, \ldots, \mathbf{m_{N_t}}\} \tag{5.18}$$

Where N_t is the number of transmit antenna or users. The detection process uses linear combinatorial nulling and symbol cancellation. The process is given below.

The fist step is to initialize the weight vector. This is given by

$$\mathbf{Z_i} = (\mathbf{HH}^* + \mathbf{2}\sigma_\mathbf{n}\mathbf{I})^{-\mathbf{1}}\mathbf{H} \ \ \textbf{for} \ \ \mathbf{i} = \mathbf{1} \tag{5.19}$$

The second step is recursive nulling and symbol canceling. This is given by

$$\begin{aligned} m_i &= \arg\ \max ||(Z_i)_j||^2 \ \ for \ \ j \notin m_1, m_2, \ldots, m_{i-1} && (5.20)\\ \mathbf{\hat{s}_{m_i}} &= sign(\mathbf{W_i^*})_\mathbf{m_i}\mathbf{x_i} && (5.21)\\ \mathbf{x_{i+1}} &= \mathbf{x_i} - \mathbf{\hat{s}_{m_i}}\mathbf{H_{m_i}} && (5.22)\\ \mathbf{Z_{i+1}} &= (\mathbf{H_{\bar{m}_i}}\mathbf{H^*_{\bar{m}_i}} + \mathbf{2}\sigma_\mathbf{n}\mathbf{I})^{-\mathbf{1}}\mathbf{H_{\bar{m}_i}} && (5.23)\\ i &= i+1 && (5.24) \end{aligned}$$

where $(\mathbf{Z_i})_\mathbf{j}$ is the jth row of $\mathbf{Z_i}$, $\mathbf{z_{m_i}}$ is the m_ith row of $\mathbf{W}$, $(\mathbf{H})_\mathbf{m_i}$ denotes the m_ith column of $\mathbf{H}$ and $\mathbf{H_{\bar{k}_i}}$ denotes the matrix obtained by replacing with zeros of the columns $m_1, m_2, ..., m_{i-1}$ of H. (5.20) is the weighting step where the strongest user signal is collected. Interference nulling is done by zero forcing algorithm as per (5.21). (5.22) is the interference canceling step. (5.23) finds the best estimate of the signal. (5.24) is the carried out for L number of users.

5.4 MIMO-SDMA-OFDM-MUD

SDMA is an application that supports multiple user communication over same band width by exploiting spatial diversity of MIMO. This results in higher bandwidth efficiency in comparison to conventional multiplexing techniques. In MIMO-SDMA-OFDM system transmitted signals received at receiver are separated by their user specific spatial signature. In other-words, user-specific spatial signature in SDMA is used to differentiate amongst the user signals . Accurate channel estimation as well as powerful Multi-User Detector (MUD) should be available at the receiver in order to support high number of users [136].

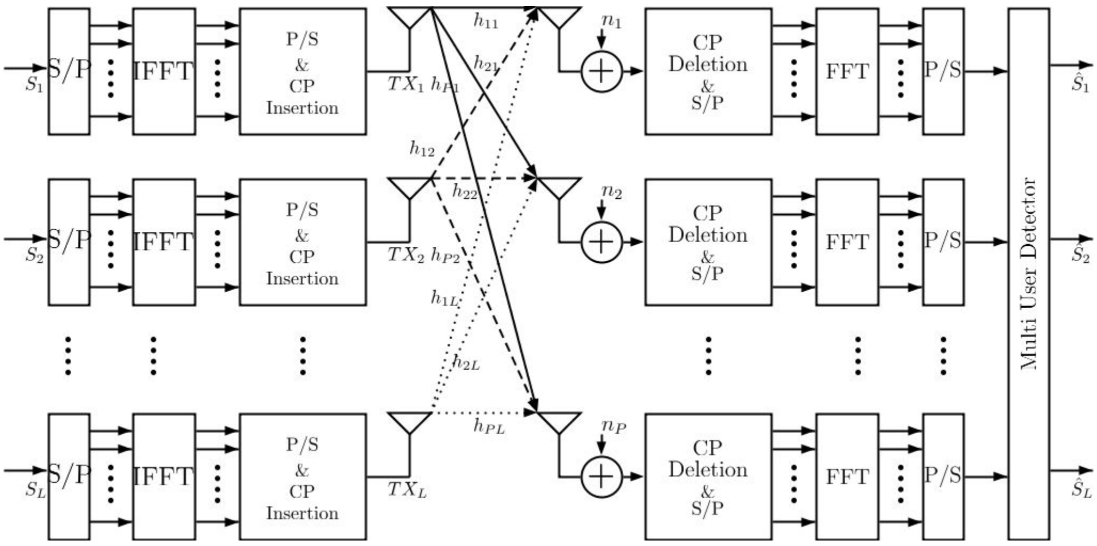


Figure 5.5: Block diagram of SDMA-OFDM Multiuser detection

Figure 5.5 shows a generic block diagram MIMO-SDMA-OFDM multi user detection. In the transmitter side, each user employs an independent OFDM block with an allotted transmit antenna. There are N_t number of transmit antennas. Similarly in the receiver side N_r number of receiver antennas are employed. Each of the receiver antenna collects N_t number of superimposed transmit signal from N_t number of users. After receiving those signals, they are processed for symbol detection similar to in OFDM system. Then data from each receiver is sent to multi user detection block. In the multiuser detection block, data are processed with the help of VBLAST decoder. In this figure VBLAST section is not shown.

Referring to Figure 5.3, 5.4 and and from (5.4), the received signal vector can be presented as

$$X = \mathbf{HS} + \mathbf{w} \tag{5.25}$$

To detect the received signals of different users, MUD schemes have to be employed at the receiver of the SDMA-OFDM system . The family of various MUD techniques includes, Maximum Likelihood Detection (MLD) [108–110,137], Parallel Interference Cancellation (PIC) [137,138], Successive Interference Cancellation (SIC) [108,109,137, 139], MMSE [108,109,137,139] and LS [137,139] detectors. Out of all the MUD detection schemes ML detection exhibits the optimum performance. Optimum performance of ML detection is achieved at the expense highest computational complexity. So, to avoid the excessive complexity of ML detection, sub-optimum detection techniques such as the MMSE-MUD have been proposed [140]. The MMSE detector has the lowest detection complexity from the group of detectors mentioned above. However, lowest computation complexity comes in compensation to BER degradation [137].

MMSE-based MUD technique uses linear MMSE combiner to estimate different users' transmitted signals. The estimated signal vector $\hat{\mathbf{S}} \in \mathbb{C}^{N_T \times 1}$ calculated from $\mathbf{s}$ of N_t users. This is accomplished by linearly combining signals of N_r different receive antenna with help of array weight matrix given as

$$\hat{\mathbf{S}} = Z^H_{MMSE}\, X \tag{5.26}$$

Where $(.)^H$ stands for Hermitian transpose. $Z^H_{MMSE} \in \mathbb{C}^{N_t \times 1}$ is the MMSE based weight matrix given by

$$Z_{MMSE} = (HH^H + \sigma_n^2 \mathbf{I})^{-\mathbf{1}} \mathbf{H} \tag{5.27}$$

$\mathbf{I}$ is the identity matrix and σ_w^2 is the variance of noise.

5.5 Evolutionary computation aided MMSE MUD

Evolutionary computation algorithms are non-gradient based optimization algorithms. The non-gradient computational nature of the evolutionary computation enable them to avoid the local minima problem that are mostly encountered by different gradient based algorithms. In other words evolutionary computation methods usually have very large solution search space that enables to find the optimum solution for a given problem.

At the receiver of SDMA-OFDM system, N_t number user's data are present with

$N_r \times N_t$ paths. So, SDMA-OFDM needs a strong multiuser detection. ML considered to be the best performing multi user detection algorithm Among many type of MUD schemes. However, it suffers from very high computational complexity. To overcome the computational overhead with ML-MUD, MMSE-MUD has been chosen by many researchers for its relative lower computational complexity. This lower computational complexity is achieved at expense of BER performance degradation. Few other MUD algorithms like VBLAST, zero forcing were already discussed in the previous section.

The preceding section discussed that the performance of MMSE MUD is not optimum in terms of BER. So, there is a scope of further enhancing the MMSE MUD performance with the use of improved training scheme. Meta-heuristic evolutionary computation methods that have ability to provide better performance. An attempt has been made here for the same.

The optimum ML MUD [141] makes an exhaustive search to find the most likely transmitted signals. Strictly, the ML MUD has 2^{mN_t} metric computations for a system with N_t number of users and m number of bits per symbol (BPS). More explicitly, for a ML-detection-assisted SDMA-OFDM system supporting L simultaneous users, a total of 2^{mN_t} metric evaluations have to be invoked, where m denotes the number of Bits Per Symbol (BPS). Detection of L-user symbol vector $\hat{S}$ that consists of the most likely transmitted symbols of the N_t users at a specific sub-carrier is given by

$$\hat{\mathbf{S}}_{\mathbf{ML}} = \arg\left\{\min_{\check{\mathbf{S}}\in\mathbb{M}^{\mathbf{N_t}}} ||\mathbf{x} - \mathbf{H}\check{\mathbf{S}}||^{\mathbf{2}}\right\} \tag{5.28}$$

where x is a $N_r \times 1$ dimensional received vector and $\mathbf{H}$ is a $N_r \times N_t$ dimensional frequency domain matrix.

In (5.28), $\mathbb{M}^{N_t}$ is constituted by 2^{mN_t} trial vectors and is given by

$$\mathbb{M}^{N_t} = \left\{\check{S} = [\check{s}^{(1)}, \check{s}^{(2)}, ..., \check{s}^{(N_t)}]^T | \check{s}^{(1)}, \check{s}^{(2)}, ..., \check{s}^{(N_t)} \in \mathbb{M}^{\mathbb{C}}\right\} \tag{5.29}$$

where $\mathbb{M}^{\mathbb{C}}$ is the set that contains 2^m legitimate complex constellation points of the modulation scheme used. Complexity of the ML detection is exponentially proportional to the number of users N_t.

Most of the linear or nonlinear estimation and detection algorithms are designed on the basis of maximizing or minimizing a linear or nonlinear relationship. This is called the cost function of the algorithm. Similarly, in any evolutionary computation, a certain relationship called Objective Function is to be minimized or maximized depending on the problem it is dealt with.

While the intention is to improve the performance of MMSE detection in MUD by using meta-heuristic evolutionary computing algorithm still the ML decision metric of (5.28) can be used to estimate the transmitted signal vector $\hat{S}_{EA}$. Here EA stands for evolutionary algorithm. For the case of a SDMA OFDM system using P number of receiver antenna, the decision metric required for each of the pth receiver antenna, called antenna-specific Objective Function (OF) [142]can be derived from (5.28). The objective function can be given by

$$\Omega_p(\check{S}) = |x_p - H_p\check{S}|^2 \tag{5.30}$$

where x_p is the symbol received at the input of the pth receiver at a specific OFDM sub-carrier, while H_p is the channel transfer function matrix H at pth row. Hence, the decision rule for the optimum MUD with the pth antenna is a specific L-symbol vector $\check{s}$ that minimizes the metric given in Equation 5.30. Thus, the estimated transmitted symbol vector of n_t users based on the received signal at the pth receiver antenna for a specific sub-carrier can be given by

$$\hat{S}_{EA_p} = \arg\left\{\min_{\check{S}}[\Omega_p(\check{S})]\right\} \tag{5.31}$$

Since the channel impulse response of each receiver antenna is statistically independent, an L symbol vector that is optimum for one receiver antenna may not be the optimum vector for rest of the receiver antennas. So, we face a decision conflict that can be expressed as

$$\arg\left\{\min_{\check{S}}[\Omega_i(\check{S})]\right\} = \hat{S}_{EA_i} \neq \hat{S}_{EA_j} = \arg\left\{\min_{\check{S}}[\Omega_j(\check{S})]\right\} \tag{5.32}$$

where $\forall i, j \in 1, 2, \ldots p$ and $i \neq j$. This decision conflict provokes to look for multi objective optimization situation. A similar decision conflict was analyzed by [143] to reconcile the decision conflicts of multiple antenna that results in decision dilemma. So, solving the decision conflict problem, an approach (as given in [143]) in which we intend to sum up the cost of each of N_r element receive antenna. Hence the modified cost can be presented as

$$\Omega(\check{S}) = \sum_{p=1}^{N_r} \Omega_p(\check{S}) \tag{5.33}$$

Hence, the decision rule for evolutionary algorithm aided MUD is to find specific L symbol vector$\hat{S}_{EA}$ that minimises $\Omega(\check{S})$

For SDMA-OFDM multi user detection, (5.33) play an pivotal role for optimisation. In the following sections we introduce Bat algorithm and it is used for assessment performance of a SDMA-OFDM system.

5.5.1 Bat algorithm

Bat algorithm is a meta heuristic optimization algorithm developed in 2010 by Xin-She Yang [144].The algorithm works on the principle based on the echolocation behavior of bats. Microbats use the capability of echolocation to find their prey and discriminate different types of insects at any time.

Most microbats live on eating insects. Microbats use one type of sonar, called, echolocation, to detect the prey, avoid any possible obstacles, and locate their crevices in night. They emit a loud sound pulse and listen for it's echo to bounce back from the surrounding objects. Different species of microbats use different pulse frequency according to their haunting strategy. Echolocation behavior of microbats can be devised to solve a problem that is associated with an objective function to be optimized. This is the driving force to formulate new optimization algorithms.

5.5.1.1 Assumptions of Bat Algorithm

The Bat Algorithm has some simple and idealized assumption. These are

1. All bats use echolocation to sense distance. Also the difference between food/prey and background barriers is known to them in some way.

2. Bats have their own position B_i and velocity V_i. They fly from one position to other randomly. They use a fixed frequency f_{min}, varying wavelength λ and loudness A_0 to search for prey. Bats have the ability to adjust the wavelength (or frequency) of their emitted pulses automatically. They can regulate rate of pulse emission $r \in [0, 1]$, depending on the proximity of their target.

3. Though the loudness can vary in many ways, it is assumed that the loudness varies from a large (positive) A_0 to a minimum constant value A_{min}

5.5.1.2 Movement of Virtual Bats

There are some defined rules to update locations B_i for bats, velocities V_i while searching in a d-dimensional search space. At any time instance 't', a set of new solutions B_i^t and velocities V_i^t can be presented as

$$f_i = f_{min} + [f_{max} - f_{min}]\beta \tag{5.34}$$

$$V_i^t = V_i^{t-1} + (B_i^t - B_g)f_i \tag{5.35}$$

$$B_i^t = B_i^{t-1} + V_i^t \tag{5.36}$$

where $\beta \in [0, 1]$ is a random vector drawn from uniform distribution variable. B_g is the current global best location. The flow chart of a Bat algorithm is given in Figure 5.6. Bat algorithm is currently gaining importance in different field of application areas in research and development [145–152].

5.5.2 Genetic Algorithm

GAs are model of machine learning or stochastic search algorithms based on the mechanism of natural selection and natural genetics. GA starts with an initial set of random solutions called population size satisfying system constraints to the problem. Each individual in the population is called a chromosome (or individual) that represents a possible solution to the problem at hand. Chromosome is a string of symbols usually, but not necessarily, a binary bit string. The chromosomes evolve through successive iterations called generations. During each generation, the chromosomes are evaluated, using some fitness value. To create the next generation, called offspring, are formed by either merging two chromosomes from current generation using a crossover operator or modifying a chromosome using a mutation operator. Usually both crossover and mutation operation are used for generation of offspring. A new generation is formed by selection, according to the fitness values, some of the parents and offspring, and rejecting others so as to keep the population size constant. Fitter chromosomes have higher probabilities of being selected. After several generations, the algorithms converge to the best chromosome, that represents the optimum or suboptimal solution to the problem.

GA [153–156] is a powerful meta-heuristic derivation free optimization tool introduced by Holland [154]. Since its inception, a growing interest in GA has resulted in rapid development of the algorithm. GA used in variety of applications both in research and industry. In this section the overall working principle of GA is analyzed.

Working principle GA consists of following steps.

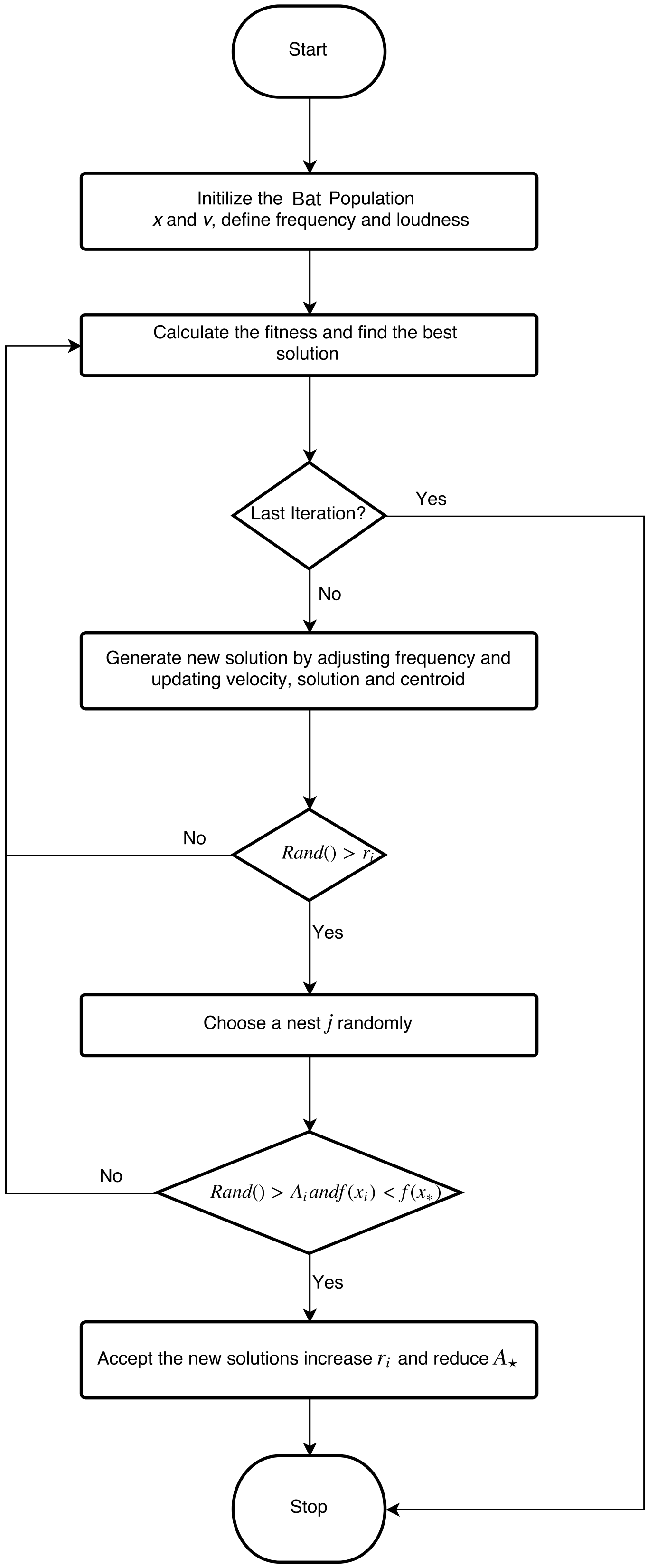


Figure 5.6: Flow chart of BAT algorithm

Population initialisation At the beginning of GA, initial population of X is created randomly. These populations are called individuals. Each individual represents a solution candidate for the search problem. Each individual has got their own chromosomes for offspring generation. Usually the number of chromosome is dimension of the search space.

Fitness value evaluation GA's task is to find a minimum (or maximum as per requirement) by employing many individuals. So each individual is a possible optimal or near-optimal solution set. Fitness of each individual is calculated with the help of an objective function.

Mating pool creation Based on the fitness score, T individuals with with highest fitness score are selected. There are many strategies for selecting the mating pool . Most popular is pareto optimality.

Selection In order to maintain the population through consecutive generations, the individual in mating pool are then selected as parents for producing offspring. The selection is based on fitness proportionate algorithm. In this stage only $X/2$ pair of parents are selected.

Cross over Each pair of $X/2$ parents are then invoked to crossover operation. Crossover is a process during which some of the genes (chromosome)are exchanged with other parents by creating two offspring. Uniform cross over is very popular.

Mutation After cross over is complete, X offsprings are generated. These offsprings are then subjected to mutation operation which changes the genes. After this process some of the offspring's gene has been changed.

Elitism cross over and mutation give the opportunity to improve the fitness. However, it never guaranteed that the offspring will acquire better fitness than their parent. So, few of the best performing high fitness parents are stored replacing some weak fitness value offsprings. This is called elitism.

GA has got vast application in different disciplines of science and engineering research. Many researches have been carried out for phase offset estimation in OFDM, channel estimation in OFDM and multiuser detection in CDMA and SDMA using Genetic algorithm. In the mean while, Bat algorithm is now in its evolving stage. Though Bat algorithm has been used to solve many of the civil and mechanical problems, its application to OFDM is not carried out till date. The flowchart of the GA is shown in Figure 5.7.

5.6 SDMA-OFDM MUD using Bat Algorithm and GA

Figure 5.8 shows the simulation model block diagram using Genetic Algorithm and Bat Algorithm. N_t number of users transmit their data independently. Data are then encoded by VBLAST encoder. After encoding process OFDM modulation is carried out. In this diagram the whole OFDM block is not shown as to simplify the diagram. The major operations of OFDM like 'IFFT' and 'FFT' are shown. The OFDM modulated data are then transmitted by N_t number of independent transmitters. In the receiver the reverse process is done as shown in the figures.

5.6.1 Bat algorithm in SDMA-OFDM MUD

The application of Bat algorithm to SDMA-OFDM multi user detection is attributed in the Algorithm 1. As presented in Figure 5.8, the system L number of users. So the multi user detection in the receiver side is required to detect L user's information. Hence, the search space dimension of the GA and Bat algorithm is L dimension.

The cost function to optimize is given by (5.33)

$$\Omega(\check{S}) = \sum_{p=1}^{N_r} \Omega_p(\check{S})$$

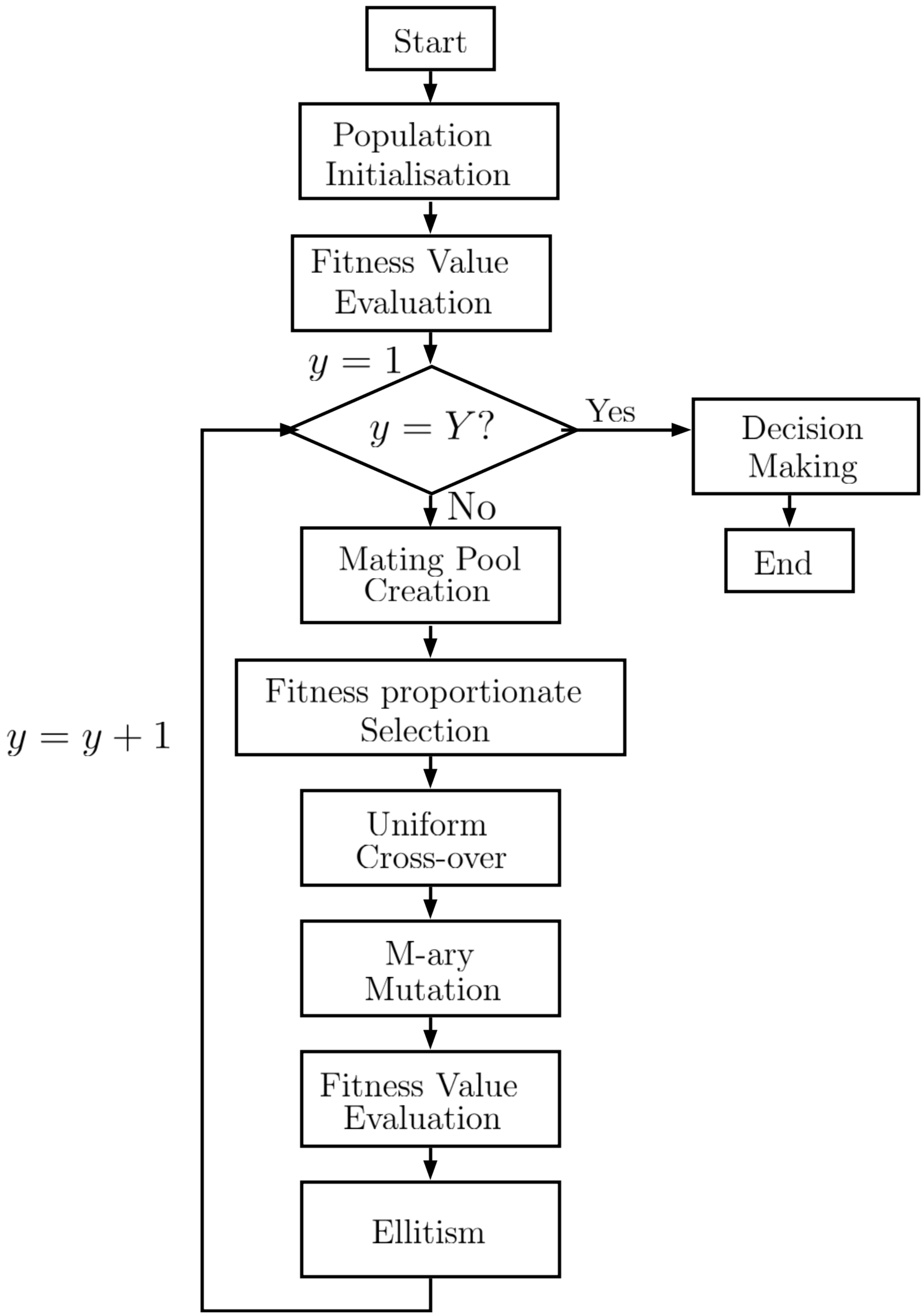


Figure 5.7: Flowchart of Genetic Algorithm

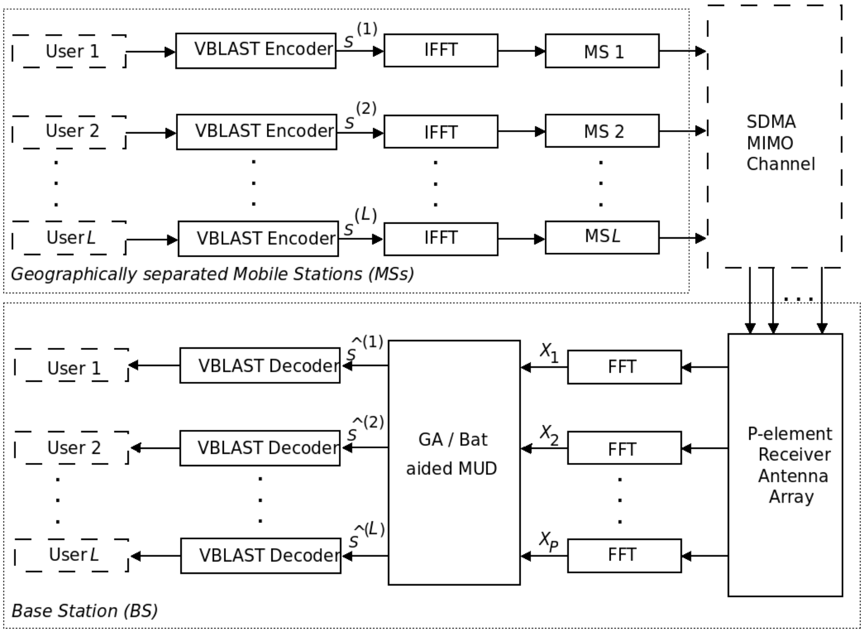


Figure 5.8: Simulation model block diagram of MUD SDMA-MIMO-OFDM with GA/Bat algorithm

Algorithm 1 Bat Algorithm for SDMA-OFDM MUD

Set the Objective Function $\Omega(\check{S}) = \sum_{p=1}^{N_r} \Omega_p(\check{S})$, $S = [s^1, s^2, \ldots, s^{N_t}]$
Initialize the bat population x_i, and Velocity v_i for $i = 1, 2, ..., n$
Set pulse frequency f_i at a locationB_i
Initialize pulse rates r_i and the loudness A_0
while (t $<Iteration_{Max}$) **do**
  Generate new solutions by adjusting frequency and update
  $f_i = f_{min} + [f_{max} - f_{min}]\beta$
  $V_i^t = V_i^{t-1} + (B_i^t - B_g)f_i$
  $B_i^t = B_i^{t-1} + V_i^t$
  if $rand > r_i$ **then**
    Select a solution among the best solutions; x_g
    Generate a local solution around the selected best solution
  Generate a new solution by flying randomly
  if $(rand < A_i \;\&\; \Omega x_i < \Omega x_g)$ **then**
    Accept the new solutions
    Increase r_i and reduce A_i
  Rank the bats and find the current best x_g
Postprocess results

Table 5.2: Parameters of Bat algorithm and Genetic algorithm

Parametrs	Method/Value	
	Bat algorithm	Genetic algorithm
population initialization method	MMSE	MMSE
Population size	20	20
Number of generation	100	100
Loudness	0.5	Not required
Pulse rate	0.5	Not required
Minimum frequency	0	Not required
Maximum frequency	2	Not required
mating pool criterion	Not required	Pareto-optimality
selection method	Not required	Fitness-proportionate
Cross-over	Not required	Uniform cross-over
Mutation probability	Not required	0.1

Table 5.3: Channel power delay profile

Delay in µseconds	Gain
0	0
10	-1
35	-1
120	-3

5.6.2 Genetic algorithm in SDMA-OFDM MUD

GA also uses the same objective function given in (5.33). It generates population size of X. Each of the population has L number of chromosomes which helps them in producing offsprings. The remaining part of the algorithm is as per the flow chart shown in the Figure 5.7.

5.6.3 Parameters for simulation

The parameter initialization for the Bat algorithm and genetic algorithm is presented in Table 5.2. The channel used in this simulation has a power delay profile presented in Table 5.4.

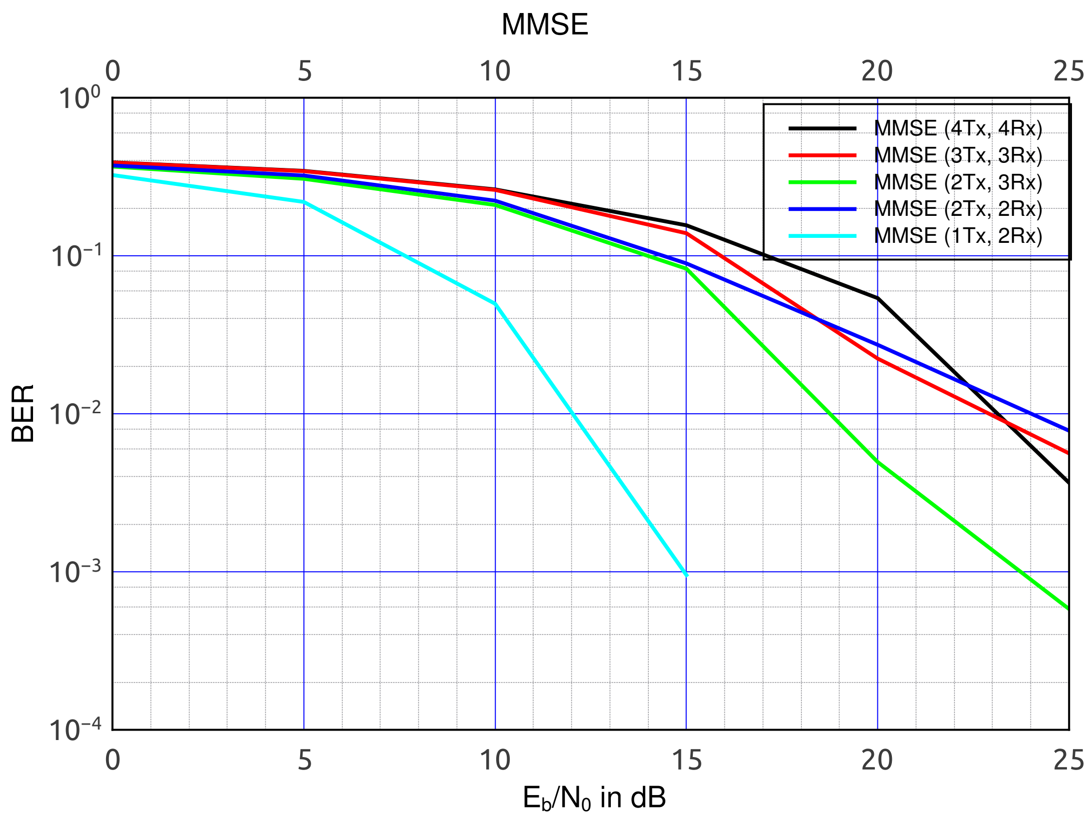


Figure 5.9: Performance of MUD SDMA-MIMO-OFDM-system using MMSE detection

5.7 Simulation Result

BER performance of MMSE detection, MMSE with GA and MMSE with Bat algorithm was carried out and the results are presented in Figure 5.9, 5.10 and 5.11 respectively. From the figures it is seen that keeping the transmitter antenna constant and increasing the number of receiver antenna give better performance. Similarly, if the number of receiver antenna is kept constant and number of transmitter antenna is increased, then the performance of the system degrades. BER performance among different algorithms are portrayed in the Figure 5.12. Looking at the figures it is seen that performance of MMSE alone is generally very poor. However, when MMSE is used as an initial solution and subsequently a meta-heuristic algorithm is used for further improvement, it gives better performance. GA was employed by Hanzo *et al.* [46] for multi user detection in SDMA-OFDM system. In this thesis Bat algorithm, a new

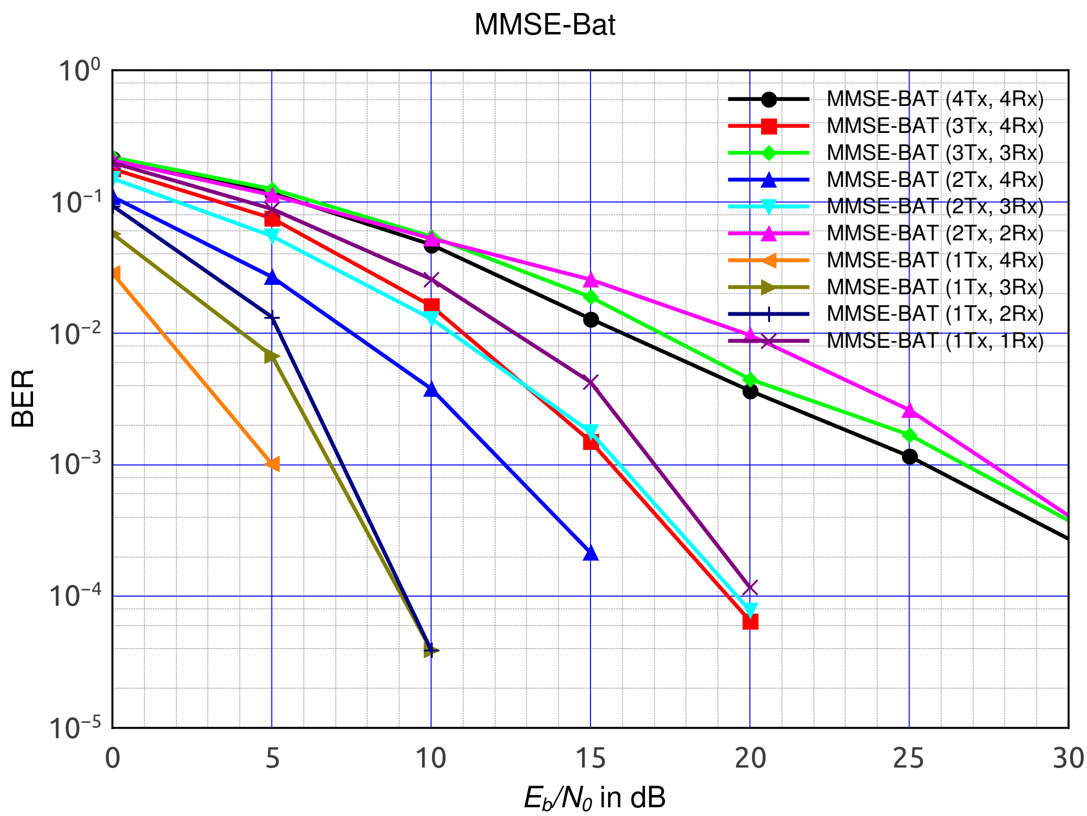


Figure 5.10: Performance of MUD SDMA-MIMO-OFDM-MMSE-BATE system

meta-heuristic evolutionary algorithm, which has been used by many researchers for better performance in variety of different applications, has been employed for multi user detection in SDMA-OFDM system. Performance of MMSE-GA and MMSE-Bat algorithm under similar evaluation condition as MMSE condition is evaluated for comparison. Figure 5.9 represents the BER performance of MMSE multi user detection for different transmitter and receiver combinations. MMSE-Bat and MMSE-GA receivers for SDMA-OFDM system for different set of transmitter and receiver antenna pairs. Performance of GA assisted MMSE receiver was shown in Figure 5.11, while Bat assisted MMSE receiver's performance was shown in Figure 5.10. A quantitative E_b/N_0 gain comparison is presented in the Table 5.4. In this table the E_b/N_0 required to achieve BER of 10^{-3} is presented. From Table 5.4 it is seen that BER performance of MMSE-Bat receiver is better improved compared to MMSE-GA receiver. From the table it is also seen that, when number of receiver antenna are

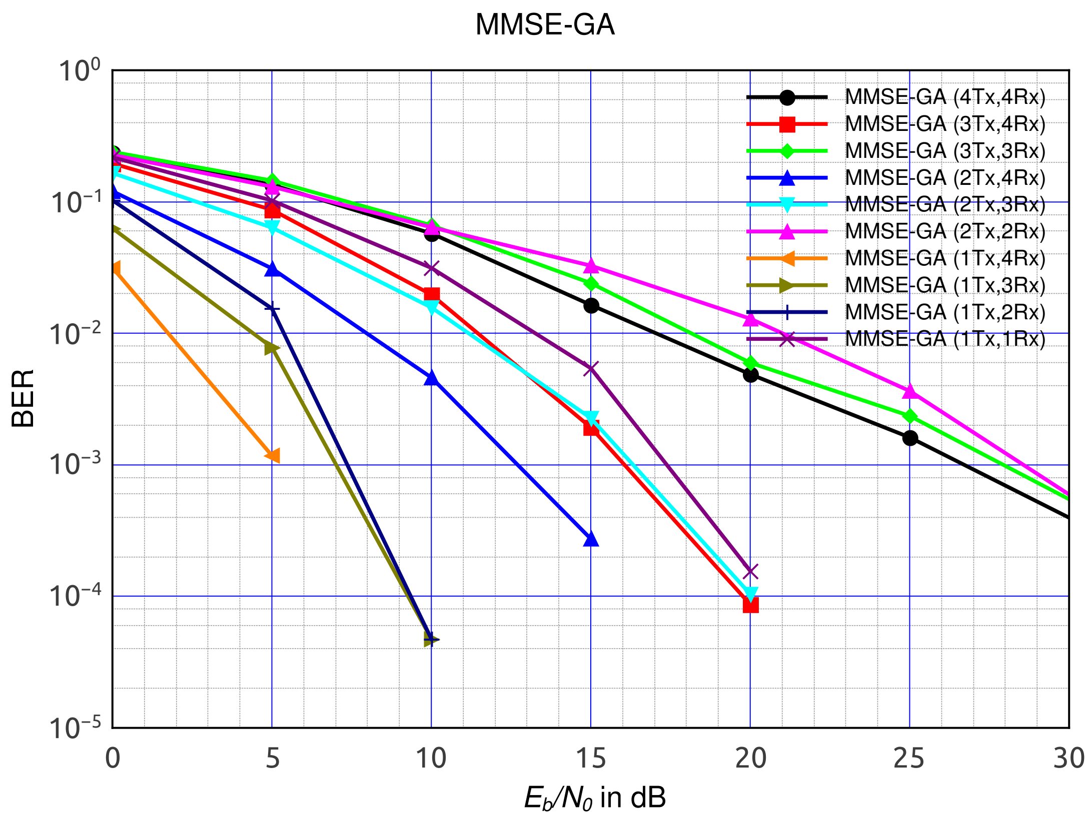


Figure 5.11: BER Performance of MUD SDMA-MIMO-OFDM GA system

increased while keeping the transmit antenna same then the performance improves gradually. It is also seen from the table that the performance difference between GA and Bat is more prominent in the case of symmetrical transmitter receiver pair combination like $2T_X \times 2R_X$, $3T_X \times 3R_X$, and $4T_X \times 4R_X$.

Table 5.4: Worst case E_b/N_0 supported for BER$=10^{-3}$ with different configuation of MIMO

$T_X \times R_X$ Combination	GA	Bat	Relative Gain in dB
1×1	17.4	17.0	0.4
1×2	7.4	7.1	0.3
1×3	7.0	6.8	0.2
1×4	5.1	5.0	0.1
2×2	28.5	27.5	1.0
2×3	16.4	15.8	0.6
2×4	12.7	12.3	0.4
3×3	27.9	26.7	1.2
3×4	16.0	15.6	0.4
4×4	26.7	25.4	1.3

Figure 5.13 shows the performance comparison of multi user SDMA-OFDM for $2T_X \times 2R_X$ scenario. Similarly, Figure 5.14 and Figure 5.15 present the performance for $3T_X \times 3R_X$, $4T_X \times 4R_X$ scenario respectively. A quantitative study of E_b/N_0 at BER of 10^{-2} and 10^{-3} was conducted and result was summarized in Table 5.5.

From Figure 5.13 and Table 5.5 it is seen that performance of MMSE algorithm is minimum. At BER=10^{-2} the measured E_b/N_0 gain of MMSE-GA and MMSE-Bat over MMSE is 3.0 dB and 4.9 respectively. Both MMSE-GA and MMSE-Bat algorithm performs better than MMSE algorithm at BER=10^{-2}. However, the measured E_b/N_0 gain of MMSE-Bat over MMSE-GA is 1.9 dB. E_b/N_0 gain at BER=10^{-3} was also measured. In this case, E_b/N_0 gain of MMSE-Bat over MMSE-GA is nearly 1 dB.

From Figure 5.14 and Table 5.5 it is seen that the measured E_b/N_0 gain of MMSE-GA over MMSE is 5.0 dB at BER=10^{-2}. The measured E_b/N_0 gain of MMSE-Bat over MMSE is 6.0 dB. However, the measured E_b/N_0 gain of MMSE-Bat over MMSE-GA is nearly 1 dB which is increasing to 1.2 dB at 10^{-3} BER.

From Figure 5.15 and Table 5.5 it is seen that the measured E_b/N_0 gain of MMSE-GA and MMSE-Bat over MMSE is 5.0 dB and 6.4 dB at BER=10^{-2}. However, their measured gains are 1.2 dB and 1.3 dB at at BER=10^{-3} respectively for MMSE-GA and MMSE-Bat algorithm.

From the above quantitative analysis based on simulation results, it is seen that the performance of MMSE is for multiuser detection in SDMA-OFDM system can be improved by additional use of evolutionary algorithm. The use of evolutionary algorithms achieve better performance by tuning the parameters. Though, MMSE-GA and MMSE-Bat performs better than MMSE receiver, the E_b/N_0 gain performance of MMSE-Bat over MMSE-GA is relatively less. The MMSE-Bat has a marginal E_b/N_0 gain over MMSE-GA algorithm. However, it is seen that $3T_X \times 3R_X$ E_b/N_0 performance difference, between MMSE-Bat and MMSE-GA, is more compared to $2T_X \times 2R_X$ performance. Similarly, performance difference in $4T_X \times 4R_X$ scenario is

Table 5.5: E_b/N_0 at BER=10^{-2} and BER=10^{-3} with different configuation of MIMO

Method	BER=10^{-2}			BER=10^{-3}		
	2×2	3×3	4×4	2×2	3×3	4×4
MMSE	24.1	23.0	22.0	-	-	-
MMSE-GA	21.1	18.0	17.0	28.5	27.9	26.7
MMSE-Bat	19.2	17.0	15.6	27.5	26.7	25.4

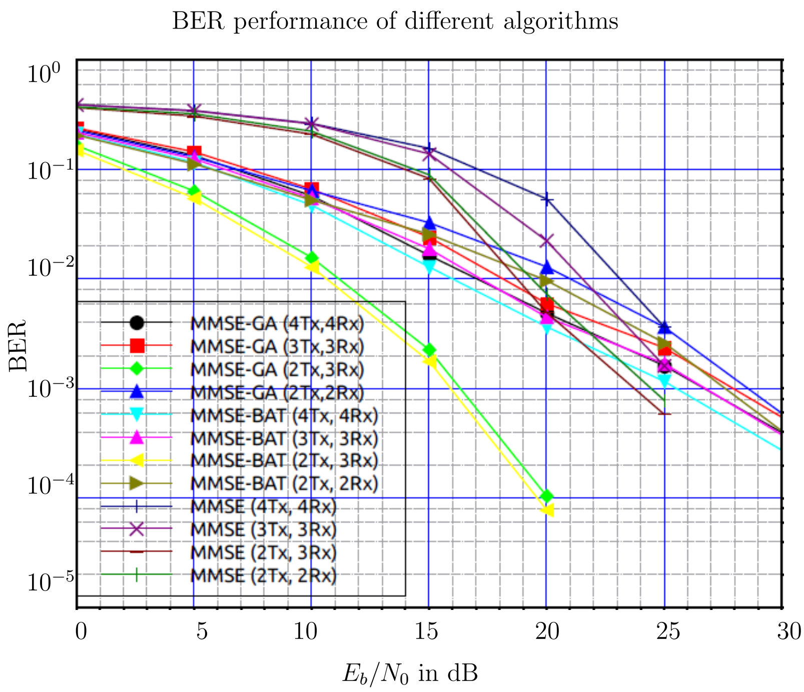


Figure 5.12: BER vs User Performance comparison of MUD SDMA-MIMO-OFDM using MMSE, GA, and BATE algorithm

even more. Hence, the symmetrical increase in transmitter and receiver antenna pair combination increases the performance difference between MMSE-Bat and MMSE-GA algorithm.

5.8 Summary

In this chapter, a detailed study of MIMO-SDMA-OFDM multi user detection was carried out. A MIMO channel model with its mathematical foundation was discussed. MIMO's ability to offer space diversity presented with its mathematical formulation. This space diversity of MIMO called SDMA was discussed with its mathematical background. Multi user detectors such as MMSE MUD, ML-MUD were discussed.

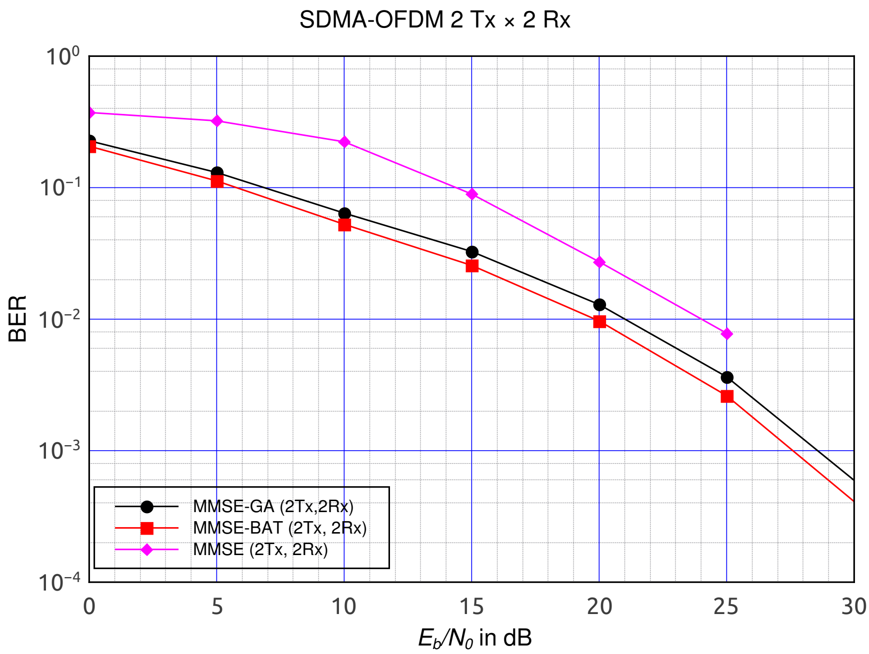


Figure 5.13: BER performance comparison of $2T_X \times 2R_X$ SDMA-OFDM system

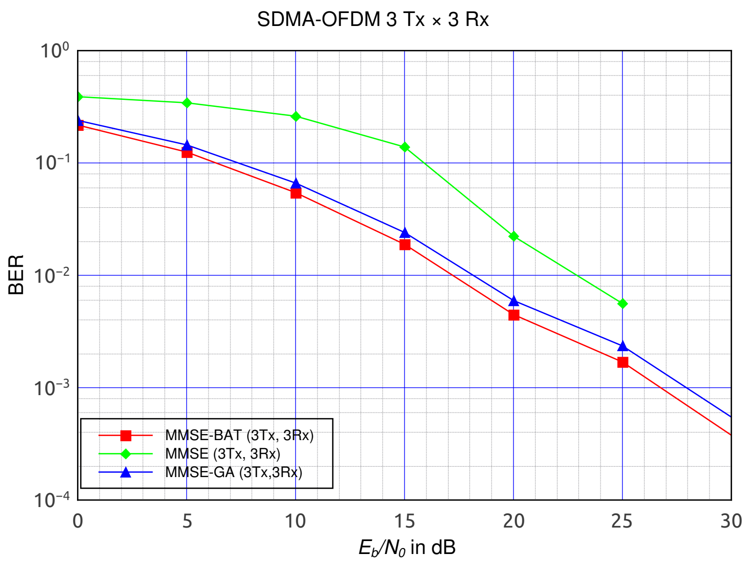


Figure 5.14: BER performance comparision of $3T_X \times 3R_X$ SDMA-OFDM system

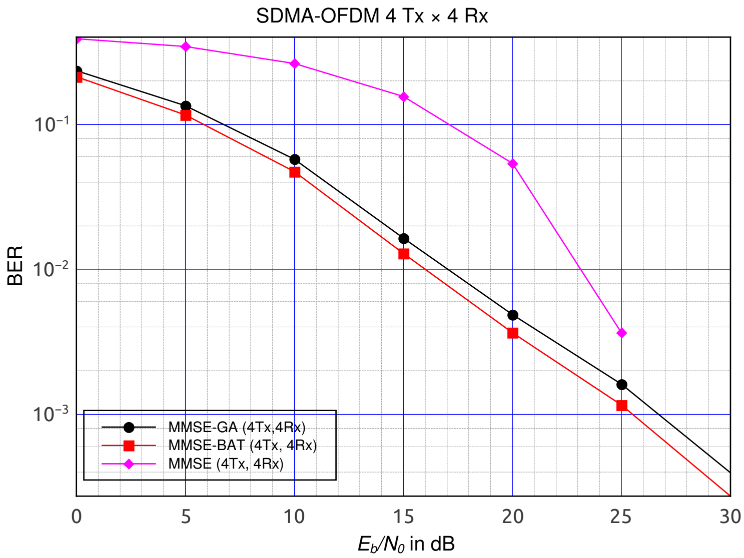


Figure 5.15: BER performance comparison of $4T_X \times 4R_X$ SDMA-OFDM system

The necessity of evolutionary algorithms for performance improvement MMSE-MUD was also presented. Working principles of different evolutionary algorithms such as GA and Bat algorithm were discussed. Finally the performance of MMSE-MUD, MMSE-GA-MUD and MMSE-Bat-MUD were compared.

6

Conclussions

"People mistakenly assume that their thinking is done by their head; it is actually done by the heart which first dictates the conclusion, then commands the head to provide the reasoning that will defend it."

Anthony de Mello

This chapter draws the conclusion for each of the objective accomplished to the thesis. Future scope of this thesis and limitation of this thesis are presented.

Contents

6.1 Adaptive boosting based symbol recovery in OFDM systems

Susceptibility of LS algorithm to noise was the driving force for this chapter. As LS algorithm is simple to implement, hence it's performance improvement can contribute a lot to the wireless technology that are especially deals with high computation. Cascading of AdaBoost algorithm with LS greatly influences the OFDM system performance. Performance of Adaptive Boosting based symbol recovery was investigated and found to be superior than the MMSE, BLUE algorithm. Performance of LS, MMSE, BLUE were also compared with the performance of AdaBoost algorithm. Out of those four estimators MMSE has higher computational complexity. Furthermore, MMSE also requires apriori channel statistics.

AdaBoost outperforms the other three algorithms which were discussed. The computational complexity of the MMSE increases exponentially as the number of carrier increases. Among all algorithms discussed over, LS has least computational complexity as it has a single vector division. So the complexity of LS is $O(N)$ with N being the DFT size. For the MMSE the computational complexity will be larger than the LS as it carries some inverse matrix operations. The MMSE receiver uses a computational complexity of $O(5N^3)$. For the Adaboost case the computational complexity calculation is little different. In the training stage, the computational complexity of the AdaBoot algorithm arises from the construction of the decision stumps and strong classifier. For the construction of the decision stumps, all samples are searched for each feature; thus, the computational complexity for constructing the decision stumps is $O(nN)$. n is the number of samples. There are T iterations for constructing the strong classifier. Therefore, in the training stage of the AdaBoost algorithm, the computational complexity is only $O(nTM)$ Furthermore, as it is a classification algorithm so in the receiver side we will require a separate de-mapper (or decoder) to get the desired data bits.

6.2 SAS aided DCT based PAPR reduction

A successive addition subtraction preprocessed DCT based PAPR reduction technique was proposed. The performance of proposed technique was evaluated. Subsequently, the performance of proposed method was compared with other pre existing techniques like SLM and PTS. The performance of the proposed method was seen to outperform specially in low PAPR region. The proposed method has low computational complexity. The complexity of the method is found to be $O(N)$. In the proposed PAPR reduction method, the receiver is aware of the transmitted signal processing, this enables a reverse operation at the receiver to extract the transmit data. Hence the requirement of sending extra information through extra subcarrier is eliminated. The proposed method is also seen to be spectrally efficient. In the case of PTS and SLM it is inevitable to send the side information to retrieve the transmit signal. Hence, these two methods are spectrally inefficient. Successive addition subtraction based PAPR reduction method was also applied to MIMO systems. The performance of the SAS based PAPR reduction method also showed better performance as compared to other technique. An extensive simulation of MIMO OFDM PAPR reduction was carried out by varying the number of subcarriers and number of transmitter antennas. A detailed computational complexity analysis was also carried out.

6.3 BATE aided SDMA multi user detection

A detailed study of SDMA system was carried out with it's mathematical analysis. Many linear and non linear detectors like ML, MMSE, PIC, SIC have been proposed in literature for multiuser detection of SDMA system. However, except MMSE every receivers other are computational extensive. So as to enhance the performance of the MMSE MUD a meta heuristic Bat algorithm was incorporated in cascade with MMSE. Here, MMSE detection symbol was used as an initial condition for the Bat algorithm. After incorporation of Bat algorithm, the system performance was evaluated. The performance of SDMA-Bat MUD, was compared with a Genetic algorithm aided SDMA-GA MUD. Performance of GA and Bat aide SDMA MUD system was evaluated for different pair of transmitter and receiver antenna. Bat algorithm performance was seen to be superior to that of the GA aide MUD system. However, the performance is more prominent and viable when the ration of number receiver antenna to number of transmit antenna is around one.

MMSE receiver suffers from severe performance limitations in such a scenarios and to enhance the performance GA and Bat tracking algorithms are seen to be effective. In this process MMSE detection training result was given as an initial solution for the input to GA and Bat optimization. By combining MMSE-GA or MMSE-Bat, it was seen that performance of the MMSE improves and the performance improvement is noticeable. However, the performance difference of MMSE-Bat and MMSE-GA are in similar scale when less number receiver antennas are employed. But the performance of MMSE-Bat algorithm improves and outperforms GA in situations when more number of receiver antennas are employed

6.4 Limitation and future work

Few of the limitations of the work are

1. The use of adaptive Boosting algorithm needs very high number samples to be trained in the training period. Once the training is over the complexity is less.

2. In the SDMA MUD system, we assumed the channel statistics are known to the receiver.

3. Computational complexity associated with GA and Bat algorithm is very high (considering they run for large number of iterations).

4. Though theoretically evolutionary algorithms finds the global solution, but it is not true alway. Some times GA and Bat algorithm stuck into local minima. Under this circumstance proper bit detection is not possible.

5. Converging speed of both GA and Bat algorithm is very high and time consuming.

6.5 Future work

1. In this thesis the AdaBoost based symbol recovery was carried out by estimating the channel through LS estimation. As MMSE performs better than LS, MMSE estimated AdaBoost symbol recovery will be carried out.

2. Though the training computational complexity of AdaBoost is high, it has less computational complexity while testing. So FPGA implementation of such a system will be developed.

3. The proposed SAS preprocessed DCT based PAPR reduction has low complexity and better bandwidth efficiency. The FPGA implementation of the proposed PAPR reduction algorithm will be developed and tested.

4. In this thesis multiuser detection in SDMA was carried by Bat algorithm. It is interesting to investigate the performance of other evolutionary algorithms such as Harmony search, Fire fly algorithm in SDMA OFDM multi user detection.

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Journal

1. Pradhan, Prasanta Kumar; Faust, Oliver; Patra, Sarat Kumar; Chua, Beng Koon, "Channel Estimation Algorithms for OFDM Systems ," *International Journal of Signal and Imaging Systems Engineering (IJSISE)*,Vol-5, issue-4, pp:267-273,2012 pub: Inderscience Enterprises Ltd.

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2. Pradhan, Prasanta Kumar; Patra, Sarat Kumar, "PAPR reduction in OFDM Systems," *International Conference on Emerging Trends and Innovation in Technology in INDICON 2014,* Pune, 11-13 Dec 2014, IEEE.

3. Pradhan, Prasanta Kumar; Faust, Oliver; Patra, Sarat Kumar; Chua, Beng Koon, "Adaptive Boosting Channel Estimation for OFDM Systems ," *International Conference on on Electronic Systems (ICES),* NIT Rourkela, Rourkela, 7-9 Jan 2011.

4. Pradhan, Prasanta Kumar; Patra, Sarat Kumar, "Performance evaluation of genetic algorithm assisted synchronous Direct Sequence CDMA systems," *5th International Conference on Industrial and Information Systems (ICIIS 2010),* pp:151-154,IEEE.

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